REDUCTION OF STARTUP EMISSIONS FOR AN ALTERNATIVE FUELED ENGINE

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for

Graduation with Honors Research Distinction

at The Ohio State University

By

Jason J. Ward

* * * * *

The Ohio State University

2013

Defense Committee:

Professor Shawn Midlam-Mohler, Advisor

Professor Giorgio Rizzoni

ABSTRACT

The reduction of emission gasses being released into the atmosphere remains an important research area in the automotive industry. In hybrid vehicle applications such as EcoCAR, engine stop/start can saturate the oxygen storage capacity of the exhaust catalytic converter. A saturated catalyst cannot effectively reduce NO_x emissions during engine stop/start and can lead to spikes in the amount of emissions being passed through the exhaust to the atmosphere. These emission spikes have the potential to be lowered considerably by using proper catalyst oxygen storage conditioning methods. The purpose of this research was to develop engine control software that will effectively condition the catalyst during stop/start events and reduce the emissions bypassing the catalyst. The developed software involves using fuel enrichment during engine stop/start and was validated on the EcoCAR E-85 engine in a dynamometer test cell. The logic resulted in a desired catalyst response during stop/start that indicated emissions bypass was being avoided.

ACKNOWLEDGMENTS

I would especially like to thank Dr. Shawn Midlam-Mohler for his guidance and knowledge during this research project. I would like to thank Dr. Giorgio Rizzoni for the opportunity to participate in this project. I would also like to thank Andrew Garcia for all his help on familiarization with engine hardware and software as well as help and advice on my project. I would like to thank the EcoCAR 2 team in general for support and guidance throughout the project. I would also like to acknowledge the financial support I received in the form of a scholarship from the Lumley Engineering Fund.

I would also like to thank my family and friends for all of their support throughout my undergraduate studies. I would not have been able to do this without them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Introduction

The automotive industry continually strives to develop new technologies to make vehicles more environmentally friendly. These innovations include hybrid or electric vehicle technologies and having more fuel-efficient internal combustion engines that produce lower emissions. The importance of this technological progress is forefront in society's move towards becoming more sustainable.

To promote and facilitate research in advanced vehicle technologies, the U.S. Department of Energy, Argonne National Lab, General Motors, and other leaders in the automotive industry develop and sponsor the EcoCAR 2 competition. In this three year competition, teams from fifteen universities across North America re-engineer a 2013 Chevrolet Malibu with the goals of increasing fuel economy, reducing overall well-to-wheel oil consumption, minimizing emissions, and maintaining performance and consumer acceptability of the vehicle. Teams design, build, integrate, and test advanced powertrain systems such as electric, hybrid, and fuel cells.

The Ohio State University EcoCAR 2 team is building an extended range plug-in hybrid-electric vehicle (PHEV). This series-parallel PHEV design incorporates an internal combustion engine coupled with an electric motor on the front powertrain and a single electric motor for the rear powertrain. The engine being used by the OSU EcoCAR 2 team is a 2006 Honda R18A3 1.8L compressed natural gas (CNG) engine that has been converted to a dedicated E-85 (85% ethanol) burning engine.

As outlined in the main goals of the competition, one of the critical tests for EcoCAR teams is the amount of emissions produced by the vehicle. These combustion emissions include carbon monoxide (CO), oxides of nitrogen (NO_x), and total hydrocarbons (THC). A catalytic converter (catalyst) is installed in the OSU team's exhaust system to help reduce the amount of emissions released by converting the emission gases into less harmful gases such has carbon dioxide (CO_2), and water (H_2O). A pre-cat (upstream of catalyst) oxygen sensor and a post-cat (downstream of catalyst) oxygen sensor are used to monitor net oxygen levels in the exhaust gas. From this, information on combustion and catalyst operation can be found and used in automated control.

1.2 Motivation

The catalyst used for Ohio State's EcoCAR application has oxygen storage capabilities like many automotive catalysts do. This means that based on combustion states (rich or lean), the catalyst can either adsorb excess oxygen in the exhaust gas or release stored oxygen to aid in the reduction process for the emission gases.

Part of the control logic for Ohio State's vehicle operation is hybrid stop/start functionality. Stop/start allows fueling to stop and the engine to completely shut down when power is not needed and spins the engine up (typically with an electric motor) to start firing again when power is needed. The purpose of this functionality is to lower overall fuel consumption and lower emissions released. However, the engine acts as an air pump during the stop/start process. Air is being pumped from when firing stops until the engine spins down to zero speed and again before firing when the engine is spinning up to operating speed. This relatively large amount of air in the system saturates the oxygen storage capacity of the catalyst. A saturated catalyst cannot effectively reduce emissions (particularly lean, or NO_x, emissions) during startup because it cannot adsorb the excess oxygen present in the exhaust. This phenomenon leads to lean emission breakthrough where NO_x is released through the tailpipe into the atmosphere.

This breakthrough of lean emissions can be the cause of emission spikes that could be seen during emission testing for the EcoCAR competition. Because the EcoCAR vehicle has stop/start functionality, these spikes could be very numerous over a city drive cycle test and could ultimately hurt the team's scoring.

These emission spikes have the potential to be lowered through a control strategy called catalyst conditioning. This strategy effectively controls how much oxygen is stored in the catalyst during startup events and, as a result, can help control catalytic conversion process to have no rich or lean emission breakthroughs. The knowledge gained from this research project and the EcoCAR competition in general could be applied to advanced powertrains in the industry to help produce better environmentally friendly vehicles.

1.3 Project Objective

The goal of this research is to reduce the startup emissions for the alternative fueled engine used in the EcoCAR vehicle. The first step in accomplishing this goal is to develop the fueling control that will have the appropriate logic to enrich fueling as well as monitor catalyst oxygen sensor readings and react accordingly. This control logic will appropriately condition the catalyst for optimum oxygen storage and effectively lower startup emission breakthrough. The next step will be to integrate this logic into the overall engine control code and perform tests in a dynamometer cell at Ohio State's Center for Automotive Research. During this time, the logic will be calibrated to optimize fueling on startup events while avoiding emission breakthrough.

The final step is to analyze the catalyst responses of the best fueling logic to determine if breakthrough has been avoided.

CHAPTER 2: LITERATURE REVIEW

The typical resultants of the combustion process in an IC engine are oxygen (O_2), water (H_2O), carbon monoxide (CO), total hydrocarbons (THC or HC), nitrogen (N_2), and oxides of nitrogen (NO_x) [7]. In order to meet government regulations and to reduce the amount of environmentally harmful tailpipe emissions released, modern exhaust systems utilize catalytic converters. Exhaust gases pass through the catalyst and, depending on the structure and coating material, harmful gases are converted to less-harmful chemicals through either an oxidation or reduction process [10].

2.1 Three-way Catalyst Overview

The exhaust system utilizes a three-way automotive catalyst (TWC) that acts as the main emissions treatment component by oxidizing unburned HC and CO emissions as well as reducing NO_x [10]. The resultants of the catalyzed chemical reactions are CO_2, N_2, and H_2O [2]. The TWC has a substrate covered by a washcoat of silica, alumina, and ceria, with noble metals platinum (Pt), palladium (Pd), and rhodium (Rh) suspended in the mixture [2]. The ceria contained in the washcoat covering promotes catalyst activity by storing and releasing oxygen based on whether the pre-catalyst exhaust gases are oxygen rich or oxygen deficient [11]. When the pre-catalyst exhaust gas mixture is lean, the ceria will adsorb the excess oxygen until it nears a saturation condition [11]. In contrast, when the pre-catalyst exhaust gas mixture is rich, the ceria will release oxygen necessary for the oxidation of HC and CO [11]. The storing and releasing of oxygen by the catalyst helps maintain stoichiometric exhaust gas conditions with low levels of HC, CO, and NOx emissions [10]. However, there is a finite oxygen storage capacity for a catalyst and the process of storing or releasing oxygen cannot continue indefinitely. When the washcoat on a catalyst tends toward the depletion of oxygen, the release rate will become insufficient for maintaining stoichiometry in a rich exhaust gas condition and hydrocarbon or carbon monoxide breakthrough can occur [10]. This situation is often avoided by closed-loop control of the engine with feedback from exhaust system oxygen sensors that allow the engine to switch between operations at lean and rich conditions [10].

2.2 Engine Stop/start

In the interest of saving fuel and lowering overall tailpipe emissions, numerous technological advancements have been employed on passenger and commercial vehicles in the past few decades. One of the more prominent techniques, especially with hybrid-electric vehicles (HEVs), is known as stop/start. While the process can vary based on the system used for each application, the main role of stop/start is to shut down the engine during idling events. This process greatly reduces idle fuel consumption over a drive cycle [1].

The shutdown event is typically triggered in vehicles by meeting certain conditions, such as vehicle speed decreasing and throttle position being zero. The engine controller or the supervisory controller (depending on vehicle application) is able to determine these conditions and send a command to shut down the engine. In a similar manner, the engine can be commanded to restart whenever any of the selected conditions are not met. Many engine restarts are completed by using an electric motor that is coupled to the engine in some manner. The electric motor typically draws power from a high voltage source (battery or capacitor pack) and spins up the engine to a minimum rotational speed needed to begin fueling for combustion [8]. For an example of the type of improvement that can be obtained by start/stop, a test based on the 1975 Federal Test Procedure (FTP) and using the 1975 urban cycle and the Highway Fuel Economy Test (HFET) drive cycle was conducted with a GMC Envoy sport-utility vehicle [1].

Bishop and Nedungadi found a 5.3% improvement in fuel economy during the city cycle, a 4.0% improvement on the highway cycle, and a 4.8% combined EPA fuel economy improvement [1].

For vehicle (particularly HEV) stop/start operation, the typical process is to stop fueling and allow the engine speed to fall to zero revolutions per minute (rpm) [8]. For some time after fueling is stopped, combustion still occurs because of the fuel film that is built up in each cylinder. Eventually, this AFR will become too lean for combustion and the engine will act as an air pump, sending air and un-burnt fuel through the exhaust system [8]. This pumping of air through the exhaust system typically saturates the oxygen storage capacity of the washcoat in the catalyst [8]. The engine is then restarted and the NOx emissions are not effectively reduced because of the saturation state of the catalyst [8]. A spike in NOx emissions is typically seen during engine restart and is only diminished when the oxygen storage level is reduced in the catalyst by rich AFR conditions or if rich conditions can be created on initial firing cycles [8].

2.3 NOx Emission Reductions

Engine startups, including those in stop/start events, can be categorized by whether they occurred with a cold engine and exhaust system or a hot (or warm) engine and exhaust system. A cold engine startup differs greatly from hot engine startup with respect to tailpipe emissions released. During cold engine startup, the catalyst is typically cold and therefore cannot effectively catalyze the chemical reactions needed to reduce NO_x emissions and oxidize HC and CO emissions [8]. To fight cold start emissions on the current EcoCAR engine, an electrically-heated catalyst (EHC) has been integrated directly upstream of the TWC [2]. The EHC has a foil structure with a typical resistance of 0.05 to 0.35 ohms and is connected to a low-voltage power source on the vehicle [2]. The pre-catalyst exhaust gases are heated by the transfer of heat from the foil structure and travel through the TWC, heating the substrate to the light-off temperature where catalytic activity can begin [2]. The location of the catalyst can greatly help reduce cold start emissions as well. In the current EcoCAR application, the catalyst is located just downstream of the exhaust manifold, next to the side of the engine block [2]. This allows heat from the engine block to soak into the catalyst and can help it achieve or maintain its light-off temperature sooner [2]. The limited length of exhaust pipe between the manifold and the catalyst greatly reduces the amount of heat lost to ambient compared to a catalyst located under the body of the vehicle [2].

Another conventional method for reducing the spike in restart NOx emissions was developed by Toyota and controls operation of the IC engine in order to reduce the amount of oxygen stored in the catalyst [6]. One facet of the strategy presented is to inject fuel within an initial period of cranking (without combustion) to cause a reduction process in the already warmed-up catalyst and reduce NOx emissions when the engine is fully restarted [6]. To help prevent excess oxygen storage in the first place, another part of the method presented is to inject fuel whenever the engine speed falls below a predetermined value and the catalyst temperature is above another predetermined value during shutdown [6].

Other methods for controlling NOx emissions have been developed that may save more fuel than Toyota's conventional method. A method has been patented by Ford that reduces the NOx emission spikes during hot start/stop events [8]. The first steps in the process of engine shutdown are to close the engine throttle and change to a rich AFR for a predetermined period of time [8]. Running with a rich AFR during engine shutdown and startup helps reduce that amount of oxygen being stored in the catalyst's washcoat [8]. By keeping the engine throttle fully closed, the amount of air being pumped by the engine is greatly reduced [8]. If the engine has an oxygen displacement valve (ODV), the next step in the shutdown process is to open the ODV so that at least a portion of the exhaust gas is diverted into the air intake when the engine is operating below a predetermined threshold speed [8]. This operation offers two main advantages over conventional approaches: it draws oxygen-depleted exhaust gas into the intake instead of oxygen-rich air and the vapor pressure inside the intake manifold generally rises to atmospheric pressure when the engine stops spinning [8]. During the restart event, the intake manifold is largely filled with oxygen deficient gas that won't contribute to catalyst oxygen storage [8]. In the next step, fueling is cut and the engine generally spins to a stop and stays in that operating state until the controller determines a restart operation is appropriate [8].

When the engine restart sequence has been initiated, the ODV is closed so that no exhaust gas is going into the air intake and the throttle opens when the engine has been spun up to a desired starting speed by an electric motor or a starter [8]. Fueling is started when the engine has reached a predetermined starting speed and a rich AFR is used for a brief period of time [8].

Furthermore, another patent by Ford describes a system for monitoring and controlling the restart NOx emissions. The system includes a first sensor for determining the oxygen level of the exhaust gas upstream of the catalyst and a second sensor for the same purpose, only located mid-catalyst [9]. If the difference between the pre-catalyst oxygen level and the mid-catalyst oxygen level exceeds a predetermined amount, the controller may close the engine throttle completely or command a rich AFR during engine restart [9].

2.4 AFR Control

AFR control is crucial to allow for complete conversion of harmful tailpipe emissions gases. Normalized AFR (λ) is described in the following equation as being the mass of fresh air (m_a) divided by the mass of fuel (m_f) and the AFR ratio for complete combustion (L_{th}) [4].

$$\lambda = \frac{m_a}{m_f L_{th}} = \frac{\frac{m_a}{m_f}}{\frac{m_a}{m_f}|_{stoic}}$$

Another equation that may be used in fueling control software is the fuel-to-air equivalence ratio (EQR), which instead takes the mass or mass flow of fuel over air.

$$EQR = \frac{\frac{m_f}{m_a}}{\frac{m_f}{m_a}|_{stoic}} \; ; \; \frac{\frac{\dot{m}_f}{\dot{m}_a}}{\frac{\dot{m}_f}{\dot{m}_a}|_{stoic}}$$

The normalized AFR (λ) needs to be maintained as close to one as possible [4]. Engine controllers use both feedback and feed forward control strategies to maintain λ and subsequently achieve stoichiometry [5]. There are inherent delays in multiple components that comprise the feedback control system for AFR, including the lambda (λ) sensor [5]. The λ sensor is a pre-catalyst universal exhaust gas oxygen (UEGO) sensor which is capable of measuring the exhaust gas oxygen content used to determine AFR [5]. The λ sensor records the oxygen content 2-20 ms after combustion occurs and as a result, no control reaction can take place until the transport delay has been completed [4]. The λ sensor is a very useful measuring device for the feedback control strategy to maintain AFR when the engine is running at steady state; but, because of the transport delay, it cannot be used for transient AFR control [5].

2.5 Summary

Control strategies for lowering startup emissions (particularly NOx) are needed to avoid unnecessary pollution. The developed, tested, and implemented strategy in the EcoCAR vehicle should be able to effectively condition the catalyst oxygen storage during stop/start events.

CHAPTER 3: EXPERIMENTAL DESCRIPTION

The facilities used for the experimentation of this research were provided by Ohio State's Center for Automotive Research. Among the accommodations used was a dynamometer test cell with a 200-hp, DC-powered dynamometer capable of both speed and torque control. Speed control was used for this research and allowed the dynamometer to motor the engine when not firing and to absorb the torque produced by the engine when firing. Within the test cell was everything needed to operate an engine, including a heat exchanger for engine coolant, exhaust fan, and dynamometer load cell. The sensors on the Honda four-cylinder engine were connected to a Woodward MotoHawk rapid prototyping, 128-pin engine control module (ECM) and INCA ETAS data acquisition system. A MotoHawk specific Simulink library was used to build control software that could be loaded onto the ECM. The exhaust system on the engine contained a prototype catalytic converter to reduce emissions. An electrically-heated catalyst (EHC) was installed within the main canister of the catalyst but was never used to pre-heat the catalyst during testing.

3.1 Engine

The 1.8L Honda four-cylinder compressed natural gas (CNG) engine was converted to use E-85 for the first EcoCAR competition. This engine was chosen for the EcoCAR application because of its high 12.5:1 compression ratio, meaning a potential for higher brake efficiency than an E-85 engine with a lower compression ratio. The engine is equipped with a variable-length intake manifold, as shown in figure 3.1.

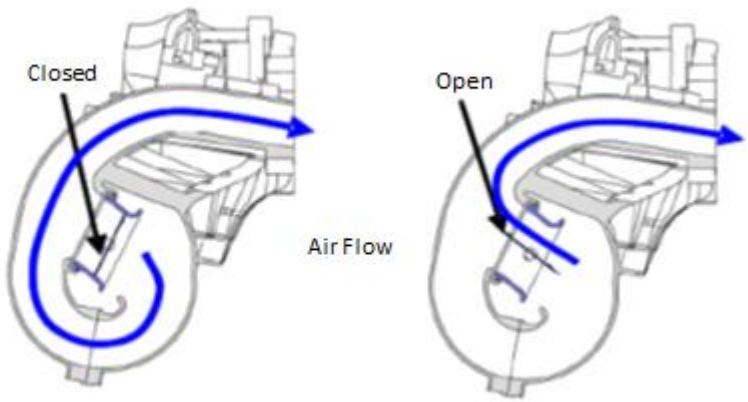


Figure 3.1 - Variable Intake Runners [12]

The runner length can be shortened by opening the bypass valve, which allows for production of more engine torque [12]. However, shortening the length that the air travels through the manifold is only applicable at higher engine speeds (around 5000 rpm) and has virtually no effect on torque production at lower speeds [12]. Since the engine speed will be limited to 3000 rpm for the majority of the EcoCAR application, the runners were set at the long distance for this research.

The Emitec catalyst is bolted directly to the exhaust manifold of the engine and there are oxygen sensors installed upstream and downstream of the main catalyst body (figure 3.2). The pre-catalyst universal exhaust gas oxygen (UEGO) wideband sensor measures the amount of oxygen in the exhaust gas immediately after leaving the cylinders. This measurement is used by the controller to give a fuel-to-air equivalence ratio (EQR) that is needed to control fueling in a closed-loop format.

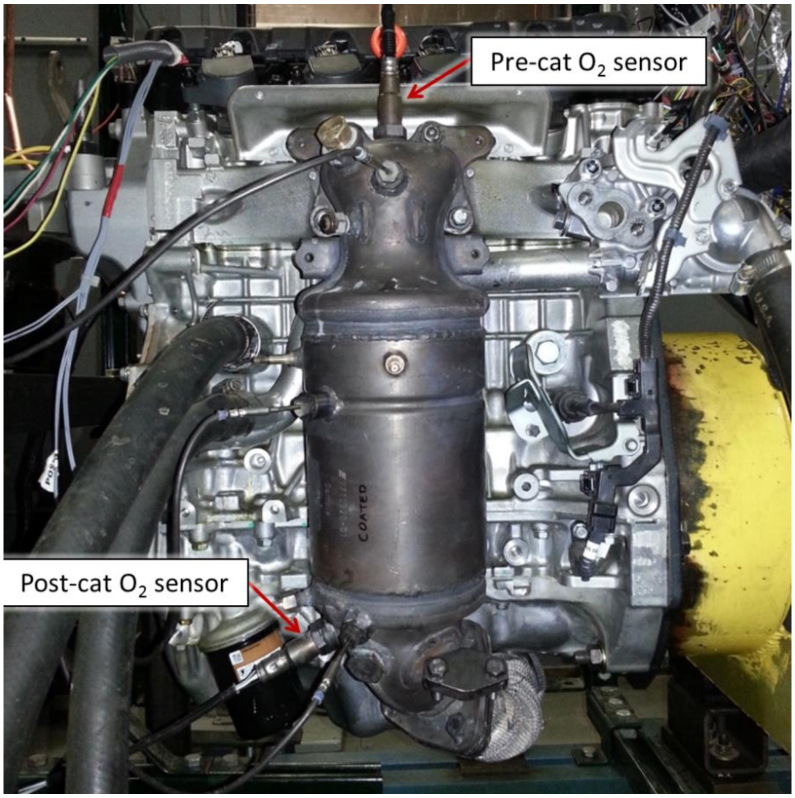


Figure 3.2 - Catalyst and Oxygen Sensors

The post-catalyst sensor is an exhaust gas oxygen (EGO) switching sensor. This sensor's signal gives a reading of how much oxygen is in the exhaust gas directly downstream of the main catalyst body. The post-catalyst EGO sensor is a switching sensor that theoretically goes between 0 and 1 V, with 0 being lean exhaust gas (excess oxygen) and 1 being rich exhaust gas (deficient oxygen). This sensor rarely reaches these extreme values, but instead stays in a range of about 150 mV to 800 mV. Previous research from the EcoCAR team has determined that the set point for post-catalyst EGO is 0.694 V [3]. The post-catalyst voltage vs. pre-catalyst EQR calibration curve of this sensor is shown in Figure 3.3.

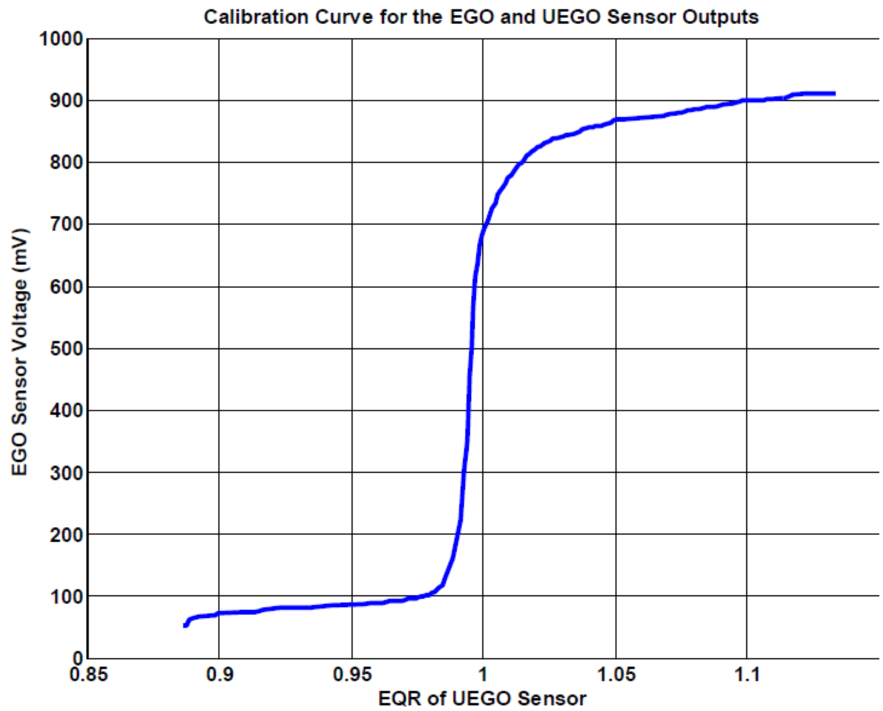


Figure 3.3: Calibration Curve for Post-Catalyst EGO Sensor [3]

3.2 Catalytic Converter

The catalytic converter used during this research was an Emitec GmbH automotive three-way catalyst coupled with the Emicat Series 6d EHC. The catalyst was mounted directly to the exhaust manifold so that it would be close-coupled to the engine. This would allow the waste heat from the engine to rapidly heat the catalyst above its light-off temperature (Bezaire, 2011). The substrate coating of the catalyst was specially tailored to the EcoCAR application and had a high cell density (400 cpsi) for a large surface area in which emission reduction reactions would take place [2]. The high cell density also enabled better heat transfer from exhaust gases and the upstream EHC [2]. Table 3.1 shows the specifications for the catalyst.

Table 3.1: Specifications for OSU EcoCAR Catalyst [2]

Manufacturer / Type	Emitec GmbH / Emicat® Serie 6d
Cell Density	400 cpsi
Substrate Type	Metal Foil
Platinum Metal Group Loading	155 g/ft^3 Pd; 15 g/ft^3 Rh
Mounting Location	Close-Coupled
Other	Electrically-Heated Catalyst
Sensors	UEGO Wideband O_2 Sensor: Pre-catalyt EGO Switching O_2 Sensor: Post-catalyst 3 Resistance Temperature Devices (RTDs): Pre-catalyst, Mid-catalyst, Post-catalyst

3.3 Data Acquisition System

The software used to during this research to run the engine and log data from sensors and the ECM was ETAS INCA V6.2. INCA communicates with the ECM via CAN Calibration Protocol (CCP), and a PCMCIA card was used to hardwire the test computer to the CCP network [3].

Four daisy-chained ETAS modules were used to read the data signals coming from the sensors on the engine [3]. This includes two ETAS ES420 modules for reading thermocouple signals via BNC cables, an ES410 module, and an ES411 module [3]. This arrangement of modules was connected to INCA with an Ethernet connection.

3.4 Methodology

The first step in developing a solution to the problem presented in this research was to collect baseline data. This data was helpful in determining how new control logic could be implemented and when this new logic would be most beneficial in the engine startup timeline. The results of this research also needed to be compared to the baseline data to verify if the steps taken to solve the emission spike issue were actually functioning as desired.

After baseline data was collected and analyzed, initial control software was developed and tested in the dynamometer test cell. Initial results were collected and analyzed from this data and more improvements were made on the software to optimize the emission reduction. The final software version was then validated in the dynamometer and prepared to be implemented in the EcoCAR vehicle.

Some important notes on the experimental design concern how the software was calibrated and what improvements could be found from this research. Cold engine startup events could not be properly calibrated with this research because the catalyst used in the dynamometer was not pre-heated as it will be in the EcoCAR vehicle. Even though an EHC was installed, the driver circuit and power supply for the EHC was not created for this project. Therefore, no way of heating up the catalyst before starting the engine existed. A cold catalyst responds quite differently from a hot catalyst. The catalyst system itself is not very stable and emission reduction reactions can sporadically occur. Because of this, post-catalyst EGO responses were not very useful for calibrating.

Although cold startup could not be properly calibrated, some improvements of cold startup could still be monitored and analyzed. This includes the time that it takes the engine to start producing positive torque after fueling begins and the general response of the catalyst over a longer period of time during startup.

CHAPTER 4: BASELINE DATA

In order to develop the fuel enrichment software, baseline data was collected and analyzed. This data was critical in gaining an understanding of how the EcoCAR specific catalyst responded to startup fueling.

4.1 Warm Stop/Start

All data collected for this thesis shared the same engine conditions, aside from engine coolant temperature (ECT) and fuel enrichment. For every test, the engine was started at 1200 rpm. This engine speed was chosen because it will be the engine idle speed for the EcoCAR vehicle when idle speed control logic is implemented in the future. Another important parameter to note is throttle position. Throttle is directly commanded by the controller as a percentage open (from 0-100%). The control logic that would be used in the vehicle automatically chooses a throttle position based on the torque requested from the controller. In the INCA interface used for dynamometer testing, the throttle position must be manually selected by the engineer operating the engine. So to select what throttle position was necessary for a speed of 1200 rpm and its associated requested torque, the 'signal' was traced through the control logic and all mathematical conversions and operations were applied. This throttle position was found to be 9% open.

Three different ECT set points were selected for baseline testing and eventual calibration of the software. These include a true cold startup (ECT < 40°C and all mechanical components are cold), a warm stop/start (ECT ≈ 55°C), and a hot stop/start (ECT ≈ 75-80°C). Three points were chosen for calibration to give better system response based on system conditions. Cold and warm engine start requires more fuel than do hot starts because the fuel dynamics changes with engine temperature. During colder conditions, fuel doesn’t vaporize in the intake runners or cylinder as fast as it will during hot conditions.

The baseline catalyst response with no fuel enrichment for the warm stop/start test is shown in Figure 4.1. A few items are worth noting when analyzing this data that will be prevalent through the rest of the data. When the fueling is shut off, the engine stops firing and is motored by the dynamometer. During this time, the engine is only pumping air. This causes the pre-catalyst EQR to dip down to around 0.17, which indicates the obviously lean conditions. This value of 0.17 is as low as the sensor conditioning circuitry goes. Since the only constituent of the gas in the exhaust at this time is air, it should read 0. Post-catalyst EGO also drops down close to zero. The control logic causes the post-catalyst signal to drop completely to zero when it’s below the threshold of 0.03. When the fuel injectors are once again enabled, there is a sharp rise in the pre-catalyst EQR. The post-catalyst EGO signal also rises up from zero when firing begins.

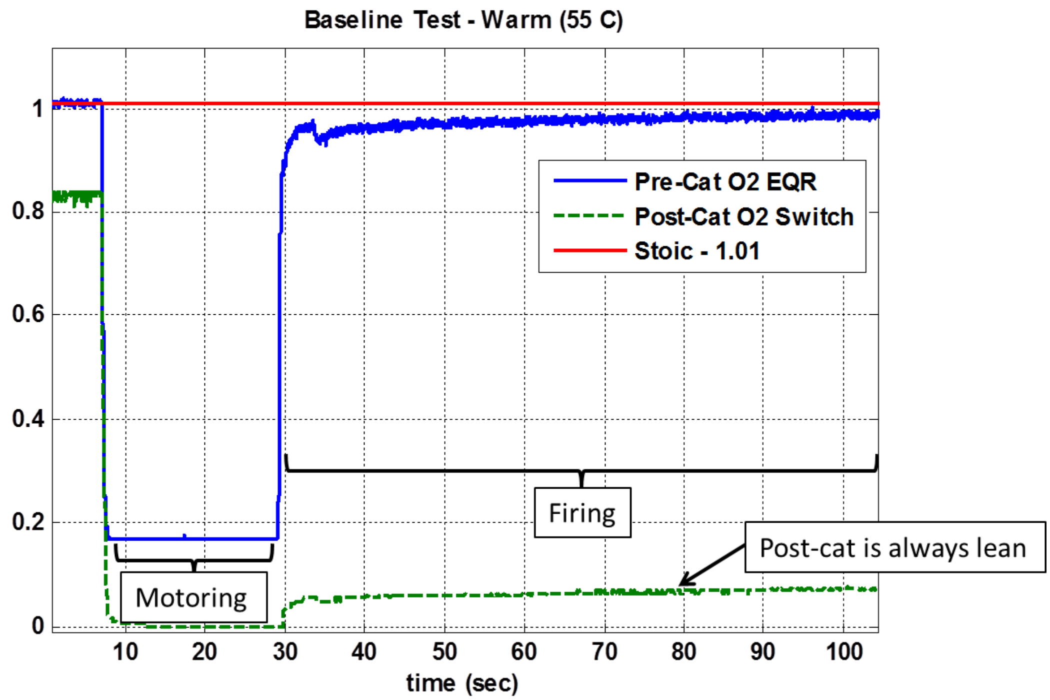


Figure 4.1: Baseline Catalyst Response - Warm

From Figure 4.1, it's apparent that during the first 70 seconds of firing, engine combustion never reached stoichiometry. As a result, the post-catalyst response stayed low the entire time and signified lean emissions (NO_x) breakthrough was occurring. This was the expected response with no fuel enrichment that causes the stop/start emission spikes. Figures 4.2a and 4.2b show the torque response from the baseline warm stop/start. The notable items include the negative torque reading from when the engine was motoring and the positive torque production from when the motor was firing. The torque response, even without fuel enrichment, occurred rather quickly. This was due to the nature of the fuel dynamics in the engine. When the engine block is warm or hot, less fuel is needed than on a cold start to build the fuel film in the intake ports before it starts evaporating. The fuel that has vaporized is used in the air/fuel mixture for combustion.

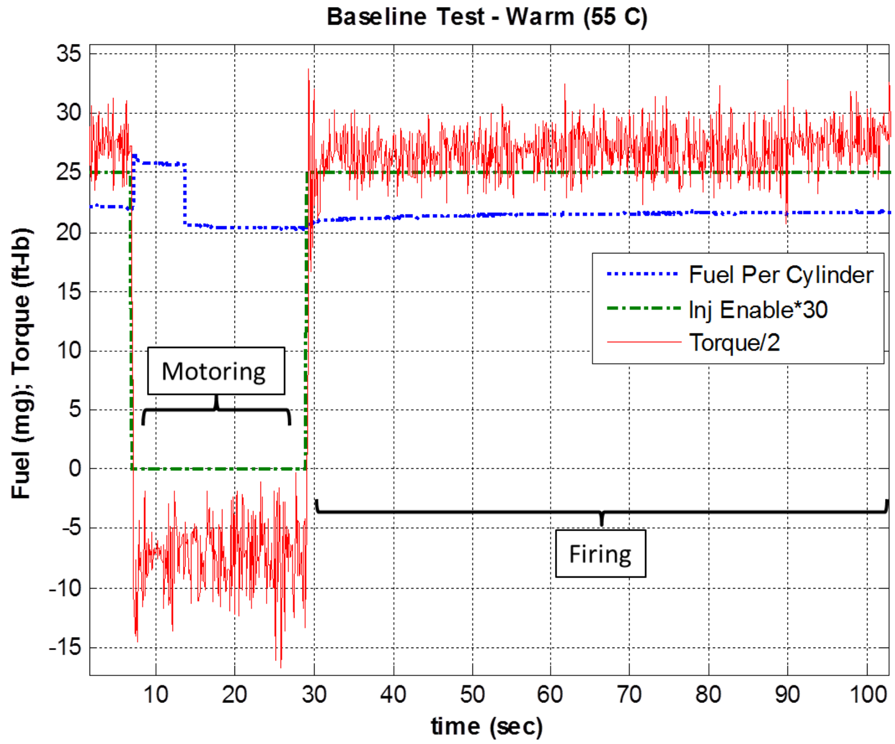


Figure 4.2a: Baseline Torque Response – Warm

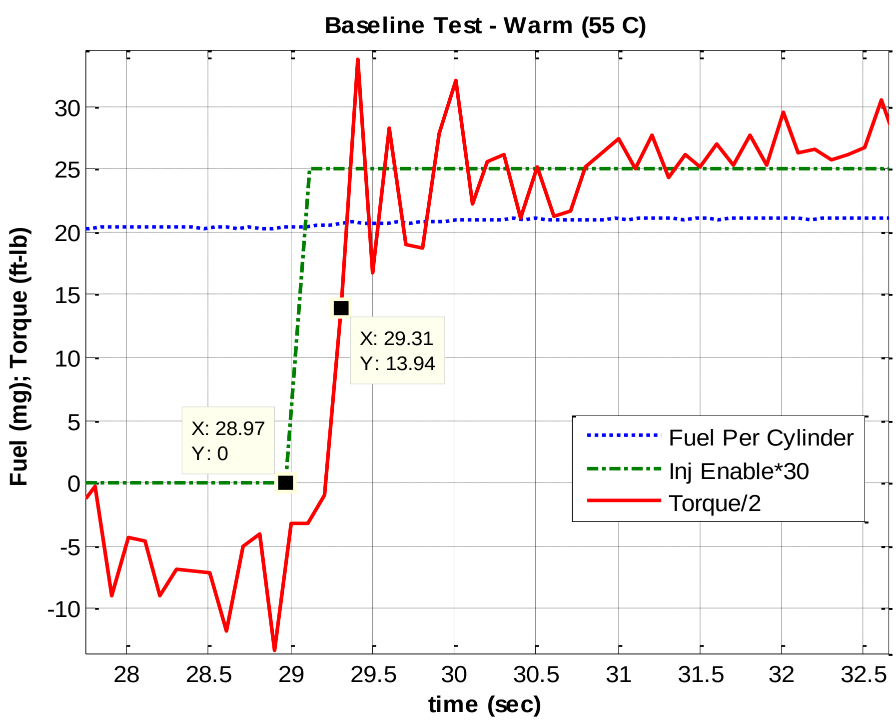


Figure 4.2b: Baseline Torque Response (zoomed) - Warm

4.2 Hot Stop/Start

The baseline test for hot stop/start was also run without fuel enrichment. The catalyst response is shown in Figure 4.3. Similar to the warm baseline, the pre-catalyst EQR takes a long time to get to stoichiometry after injectors are enabled and fueling begins. While the post-catalyst response does rise a little more than the warm did in Figure 4.2, the value still stayed below 0.2 for the 70 seconds shown after startup. This means that once again, lean emissions were bypassing the catalyst and being sent out the tailpipe. The torque response from the baseline hot test is shown in Figures 4.4a and 4.4b. As with the baseline warm results, the torque response occurred rather quickly because of the nature of the fuel dynamics.

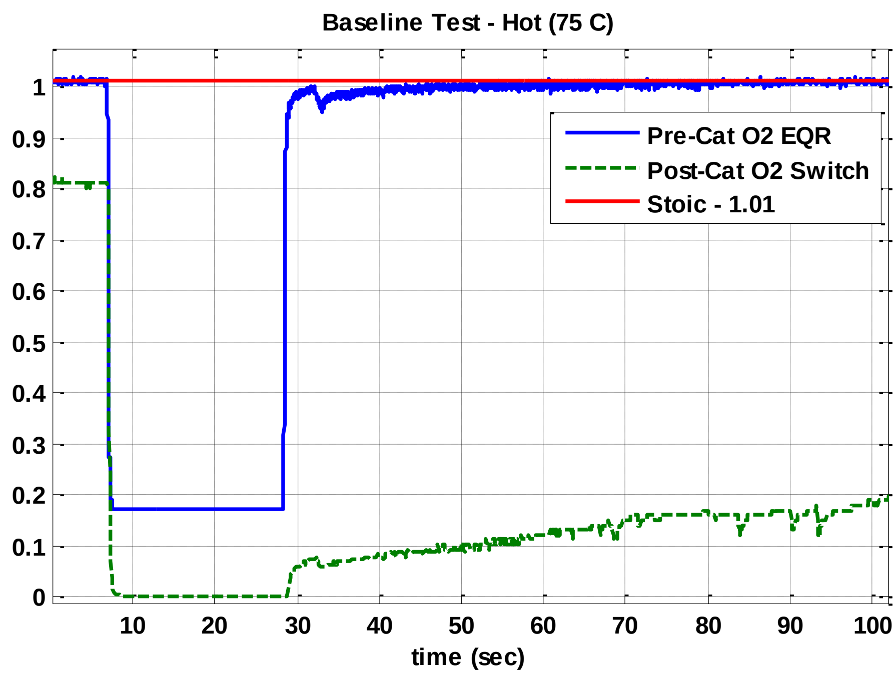


Figure 4.3: Baseline Catalyst Response – Hot

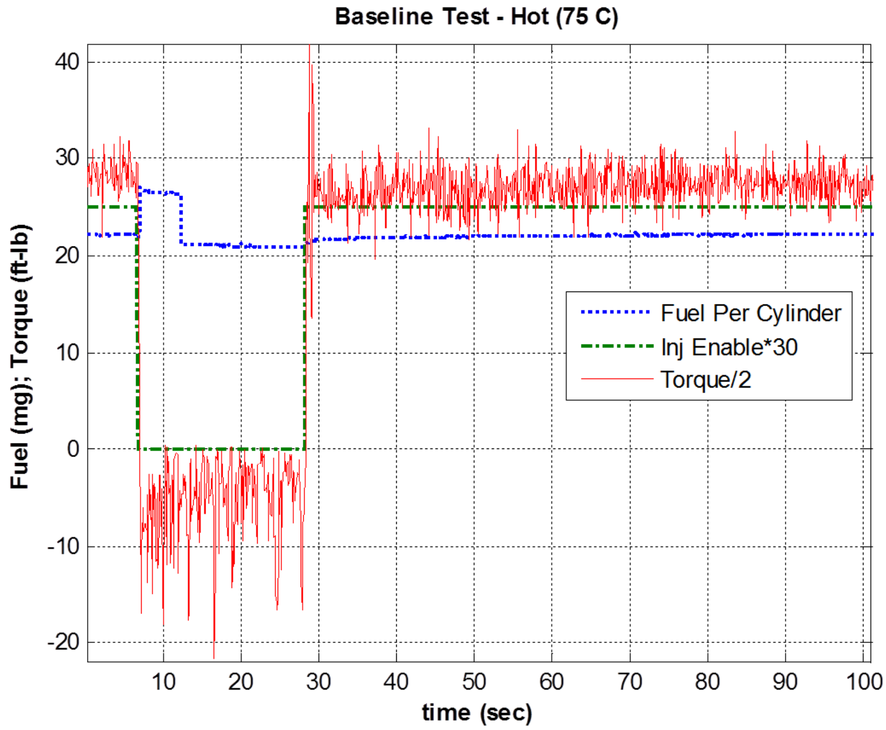


Figure 4.4a: Baseline Torque Response – Hot

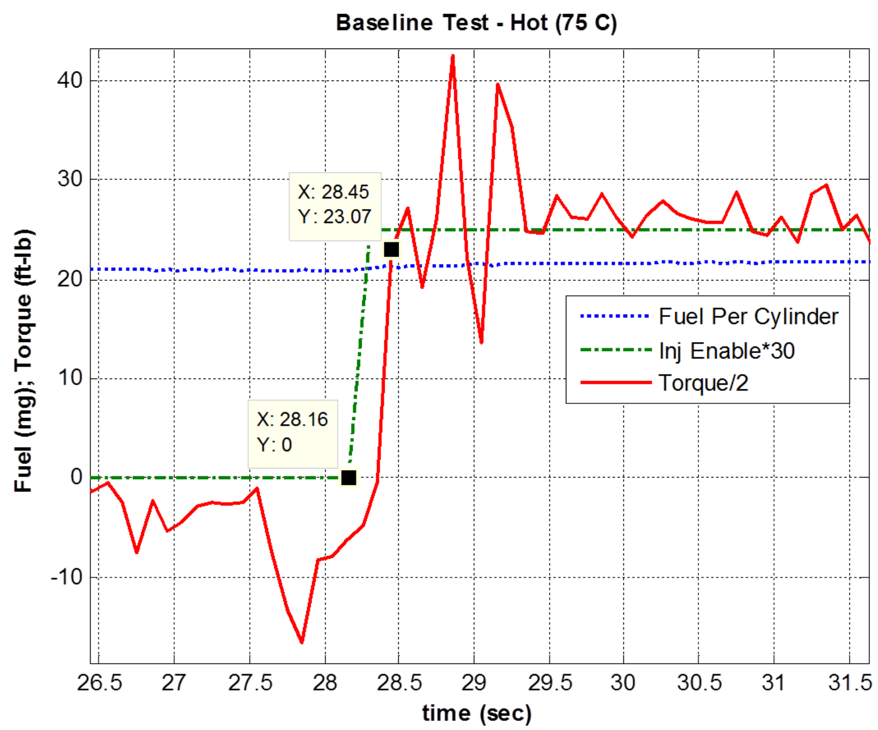


Figure 4.4b: Baseline Torque Request (zoomed) - Hot

4.3 Cold Startup

Baseline data was also recorded for cold startup with no fuel enrichment, even though proper calibration was unable to be completed for it through this research project. The plot of the catalyst response in Figure 4.5 shows a dissimilar response from what was observed during the warm and hot stop/starts. The pre-catalyst EQR has an extremely slow rise towards stoichiometry and doesn't reach stoichiometry in the 70 seconds shown on the plot. As expected and as it was with both warm and hot stop/start, this result shows that there is lean emission bypass occurring. There is a slight 'blip' on the post-catalyst EGO sensor response, but that is likely due to the instability of the catalyst since it was not at light-off temperature.

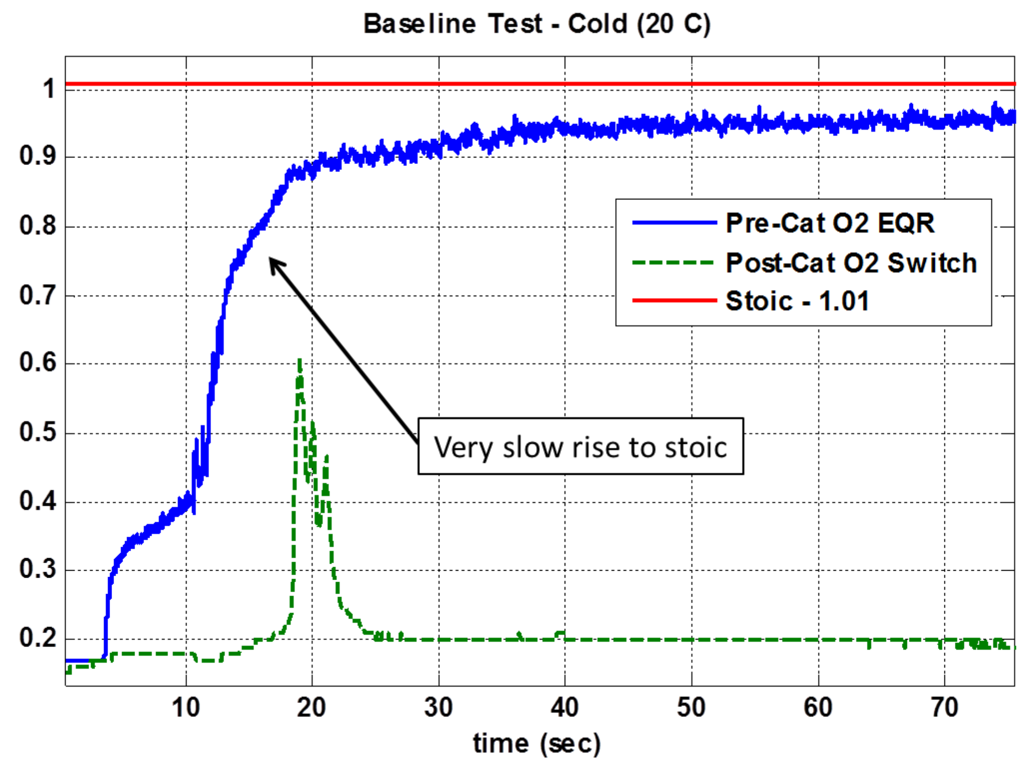


Figure 4.5: Baseline Catalyst Response – Cold

The torque response for the baseline cold test, shown in Figure 4.6, is also quite different from the responses seen from warm and hot engine condition. The engine does not start delivering positive torque for over five seconds after fueling begins. Even when torque crosses over zero, it fluctuates between positive and negative torque for a few seconds before going positive for the rest of the startup. After going positive, there is a very slow rise before torque finally reaches the desired value around 40 ft-lbs. The cause of this response is cold start fuel dynamics. When the engine block is cold, more fuel mass is needed to build the fuel film in the intake ports before fuel can evaporate and be used in combustion.

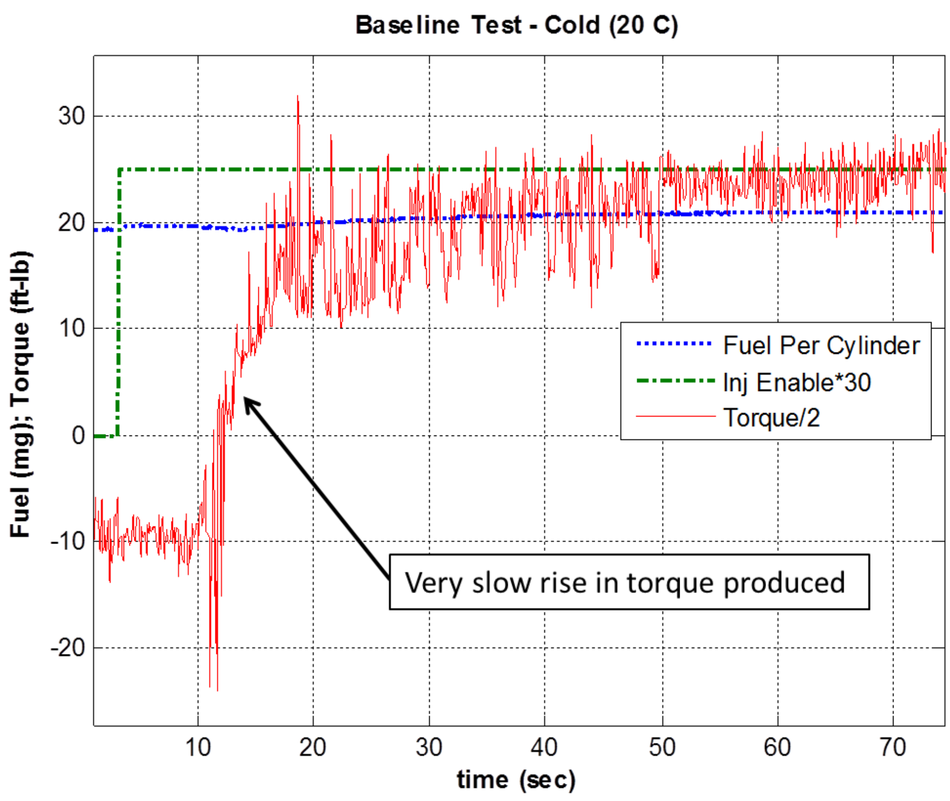


Figure 4.6a: Baseline Torque Response – Cold

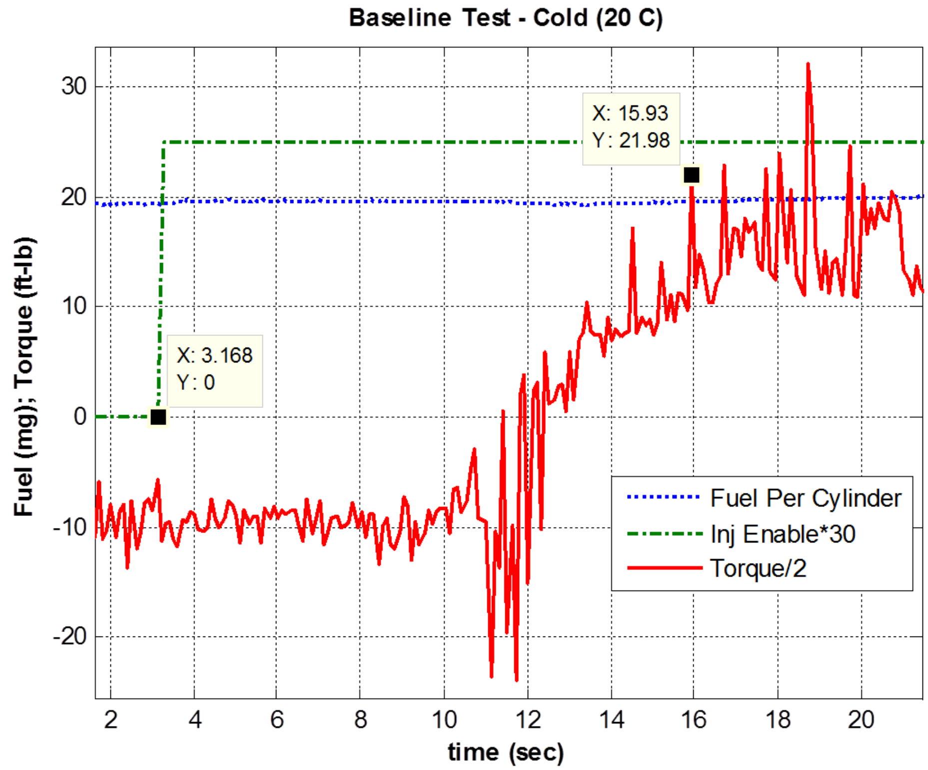


Figure 4.6b: Baseline Torque Response (zoomed) - Cold

4.4 Conclusions from Baseline Testing

From the analysis of this baseline data, a few conclusions were drawn that helped set up the development of the new software. An initial fuel spike would be very beneficial to engine performance and emissions. This spike would help build the fuel film inside the ports faster by adding more fuel, help produce positive engine torque sooner, and bring the pre-catalyst EQR closer to stoichiometry faster. This rich spike in fuel would also work to use up some of the stored oxygen in the saturated catalyst and help avoid lean emission breakthrough. Depicted in Figure 4.7 is an ideal startup with desired pre-catalyst, post-catalyst, and torque responses.

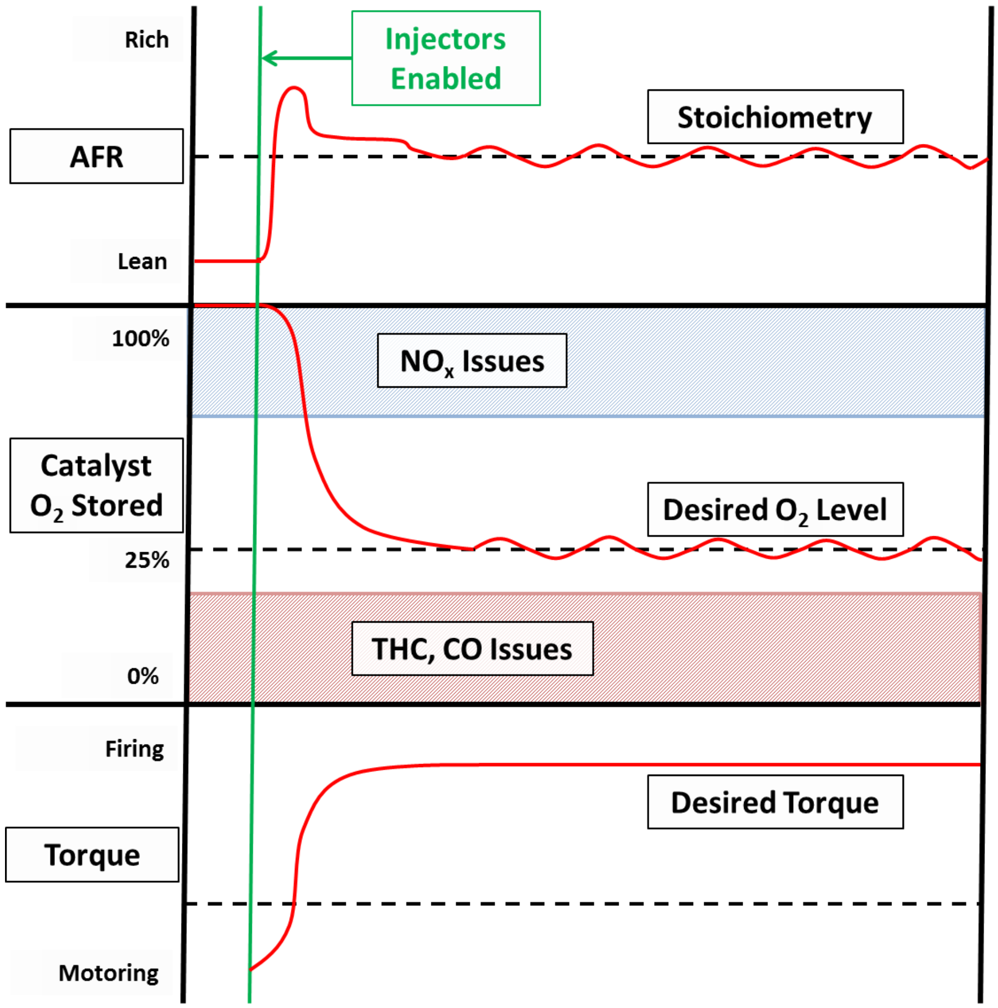


Figure 4.7: Ideal System Responses

In this response, the engine runs rich for a few moments after startup due to the fuel spike. This causes depletion of stored oxygen and also causes a quick increase in torque. The engine then operates under smaller enrichment to further use up stored oxygen until the desired oxygen level is achieved. Then regular feedback, closed-loop control takes over. This ideal setup was the goal of the software developed during this research project.

CHAPTER 5: SOFTWARE DEVELOPMENT

Based on the results taken from baseline testing with no fuel enrichment and the desired ideal response of Figure 4.7, software was able to be developed and focused to certain areas of the startup process. This was then developed in Matlab R2008a (for compatibility with ECM) using Simulink and a MotoHawk-specific block library. The initial algorithms were tested and adjustments made in an attempt to optimize the catalyst conditioning capability of the software.

5.1 Simulink Fuel Enrichment Model

The starting point for the new logic was reviewing old fuel enrichment logic that had been developed in the previous EcoCAR competition. This logic was not being used on the EcoCAR engine because its main purpose was to start the engine faster and deliver positive torque sooner. This logic was not able to appropriately condition the catalyst during a startup event. However, the new fuel enrichment logic was initially designed to deliver approximately the same fueling profile as the original software as a starting point. The eventual fueling profile for startup events is a calibrated adaptation of the initial profile. Figure 5.1 shows the ramp-down profile of the commanded fuel per cylinder for a startup event using the original software.

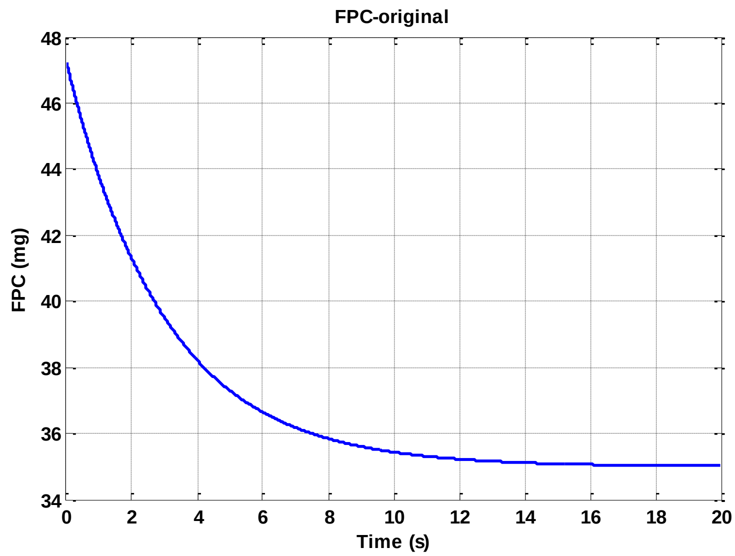


Figure 5.1: First-Order Ramp-down Initial Profile of Commanded Fuel Per Cylinder

The initial algorithm logic is summarized with the flow chart in Figure 5.2. Once injectors are enabled, the engine operates under an open loop control that causes enrichment to build the fuel film in the intake ports and deplete stored oxygen in the catalyst. Once the logic reaches a timeout or enrichment ramps down to zero, regular closed loop control of the fueling begins.

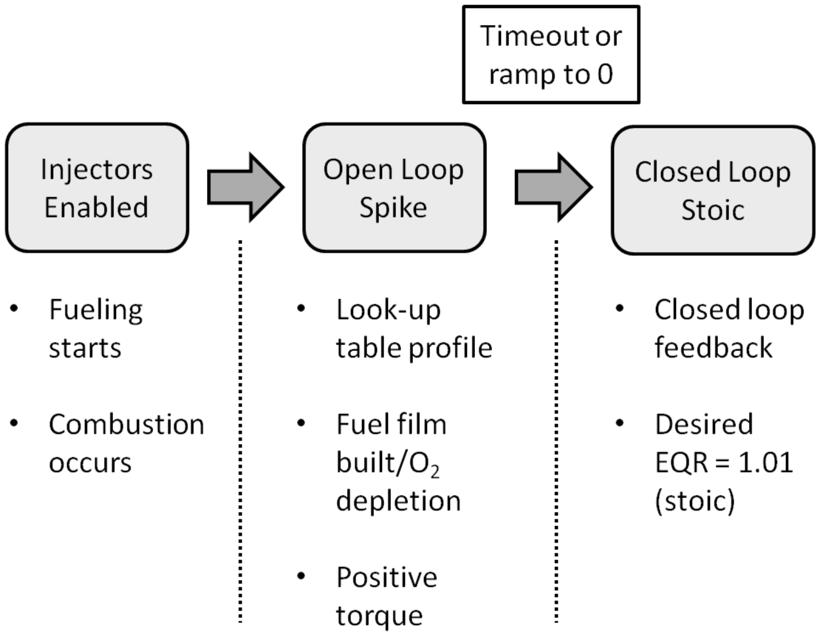


Figure 5.2: Initial Algorithm Logic

A fundamental part of the new enrichment logic used to achieve the first-order ramp-down was the one-dimensional look-up table. This block was found in the MotoHawk specific Simulink library and is shown below in Figure 5.3.

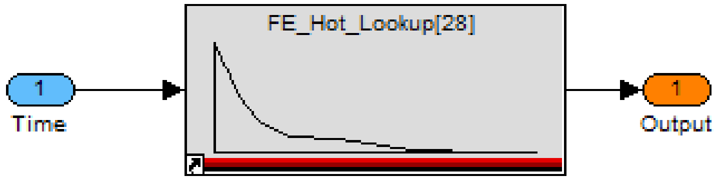


Figure 5.3: MotoHawk Look-up Table with Input/output

The one-dimensional look-up table matches a single input value to a single output value and passes through the output. This is done by initially setting up breakpoint and table data in the block parameters. Breakpoints (Figure 5.4) are individual numbers contained within a vector and are used as interpolation points for linear interpolation. The table data vector, also in Figure 5.4, includes the output value associated with the interpolation points of the breakpoint vector. Using a lookup table allowed for more flexibility than a first-order ramp-down profile, and this flexibility was needed later in the project.

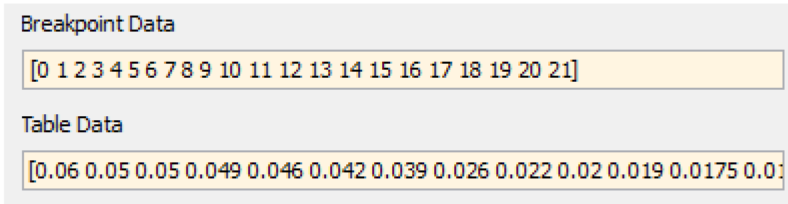


Figure 5.4: Breakpoint and Table Data Vector Examples

The input to the block diagram does not need to be at one of the breakpoints because the block performs linear interpolation between breakpoints. The input used for the new control logic was a 'time since injector enable' in which a timer was started when injectors were enabled, signaling a startup event. The output of the table was an offset that was later added to constant of one. This combination of '1.0 + offset' was then multiplied by the commanded fuel per cylinder (FPC), as depicted in Figure 5.5.

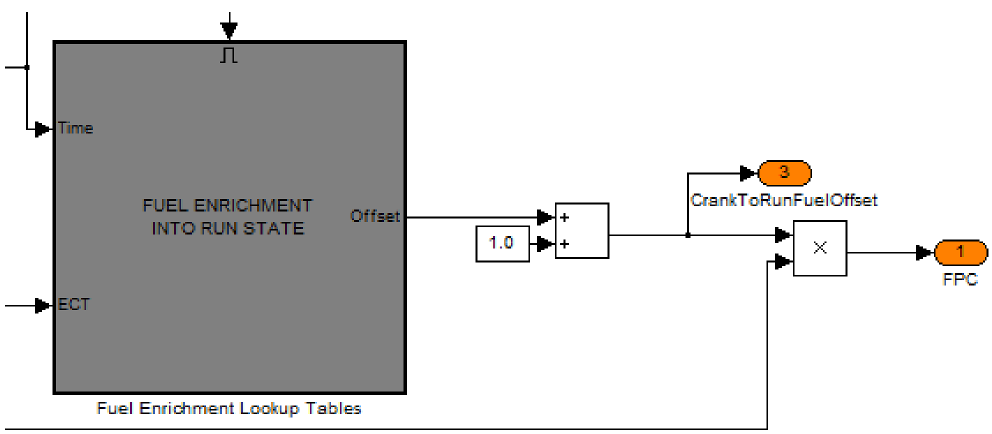


Figure 5.5: Multiplication of FPC

In order to calibrate fuel enrichment for the different engine temperature operating conditions, three look-up tables were created with three different ranges of engine coolant temperature (ECT), shown in Table 5.1.

Table 5.1: Engine Condition Temperature Ranges

Engine Condition	Temperature Range C	
	Low	High
Cold Start	-	40
Warm Start	40	70
Hot Start	70	-

After being developed, the look-up table logic was integrated into the overall control model for the engine. To do this, the look-up tables were placed in an enabled subsystem that would enable when injectors enabled. This subsystem became disabled either when the timer measuring ‘time since injector enable’ reached 20 seconds or when injectors were disabled. As a safety precaution for initial testing, the original fueling logic (including the original fuel enrichment code) needed to still be in place in case the new logic failed. The new logic was then placed into the model in parallel to the original fuel enrichment, both within separate enabled subsystems. It was designed in this manner so that a switch could be thrown during testing and there could be an easy shift from the old fueling logic to the new logic.

In order to flash the new control model onto the MotoHawk ECM in the dynamometer test cell, it was converted into compiled binary code by a process called ‘building’. After the conversion process took place, the compiled code was flashed onto the ECM using the Moto Tune ECU Calibration Tool. Because no special engine instrumentation was needed, the new logic was able to be immediately tested.

5.2 Initial Testing and Results

The testing started with the replica of the original fuel enrichment profile. Following the testing description, the experiments were run at 1200 rpm and 9% throttle. After analyzing the results of that test, the enrichment profile was adjusted by changing the values of numbers in the 'Table Data' vector of the look-up tables. This served as an attempt at optimizing the amount of fuel needed as a function of time after injectors were enabled during a startup procedure. This process was repeated numerous times within all three of the ECT ranges.

Eventually, it became difficult to fine-tune the enrichment profile further. The 'best' experimental results for each temperature range showed some significant improvements over the baseline testing. However, it was evident that better fuel enrichment control was needed to be able to condition the catalyst to a satisfactory result.

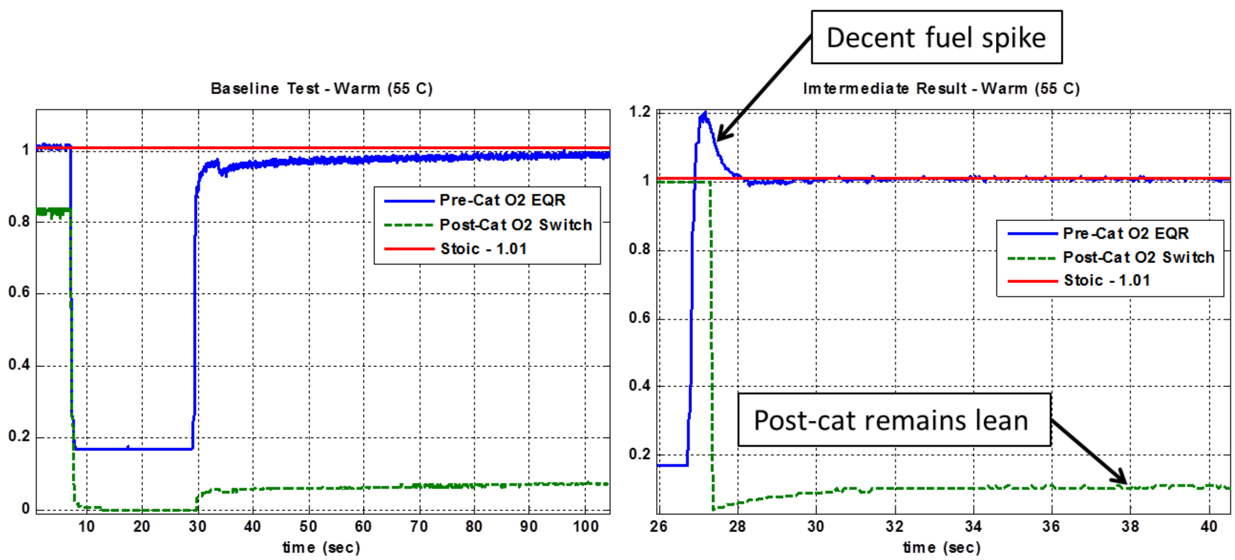


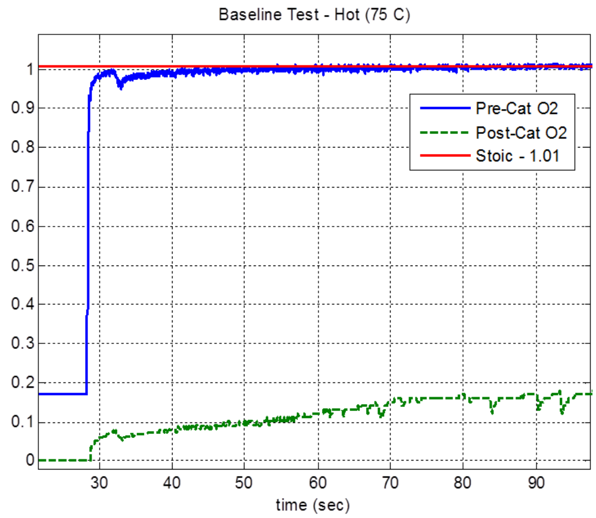
Figure 5.6a: Baseline Result (Warm) **Figure 5.6b: Initial Testing Result (Warm)**

Figure 5.6: Comparison of Initial Testing Result - Warm (55 C)

The result of the warm test (Figure 5.6b) shows promise in the pre-catalyst EQR response. The high initial set point for the fuel enrichment profile was able to deliver a rich spike above stoichiometry for the pre-catalyst EQR response in Figure 5.6b. This spike indicates that rich combustion occurred for approximately one second. Due to the shape of the profile, the enrichment ramps quickly down to almost zero and results in the EQR response following the spike.

Unlike the baseline test, the EQR remains steady around stoichiometry, but the quick ramp-down of fueling resulted in the catalyst not being properly conditioned. This was determined by looking at the post-catalyst EGO sensor response. This response rose to around the same value as the baseline test did and never got any higher. With this value being close to zero, it was concluded that the oxygen stored in the catalyst was not properly used up during the start of the engine and lean emissions were bypassing the catalyst.

The tests conducted in the hot ECT region showed very similar results to the warm region, as shown in Figure 5.7. Again, the initial spike of fuel and ramp-down are not able to bring the oxygen saturation level of the catalyst down. As with the warm results, this indicates that there was lean emission breakthrough.



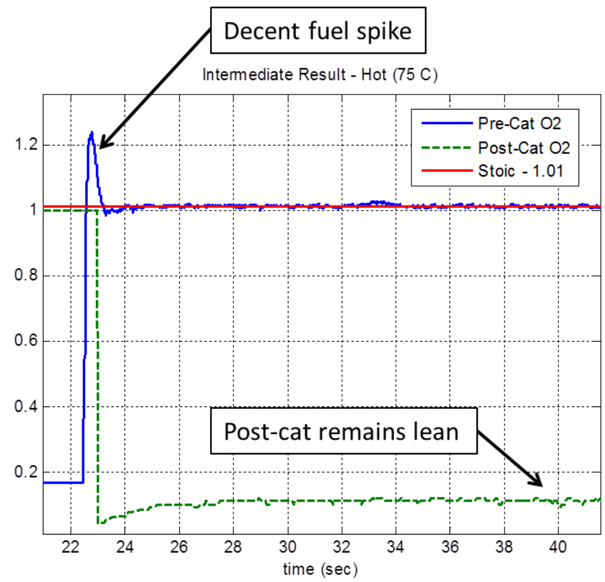


Figure 5.7a: Baseline Result (Hot) **Figure 5.7b: Initial Testing Result (Hot)**

Figure 5.7: Comparison of Initial Testing Result - Hot (75 C)

Upon inspection of the control logic, possible causes of these poor results were determined. The fuel enrichment was turned off after a set time (20 seconds after the injectors were enabled) rather than based on the response of the system. This inherent property of the open-loop control meant that the catalyst was likely to never be properly conditioned. Even if the logic were to have been calibrated to condition the catalyst at a set point temperature within a range (ex: 75 °C for the hot range), the logic would not be robust enough to entrust with conditioning the catalyst at a slightly lower temperature that would demand slightly more fuel enrichment. A cause for concern could also be brought up about the possibility of over-enrichment. If the logic was calibrated for the same set point (75 °C) and the engine temperature were actually around 80 or 85 °C, there would be too much fuel enrichment. This would cause the catalyst to use up its stored oxygen too quickly and would allow for rich emission breakthrough.

5.3 Software Improvements

Based on the results from the initial fuel enrichment testing, improvements were made to the control logic that would condition the catalyst better. This included creating higher resolution in the look-up tables, changing how the open-loop fuel enrichment was disabled, and enabling new closed-loop fuel enrichment. The process that these improvements created is shown in Figure 5.8 and explained in this section.

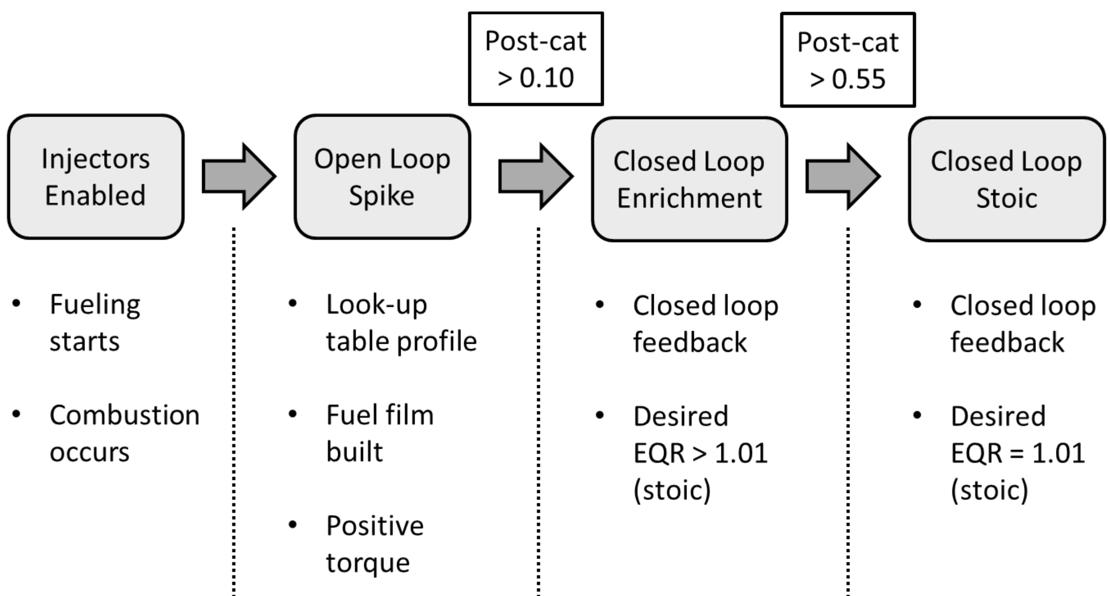


Figure 5.8: Algorithm Logic Flow Chart

While the look-up tables proved to be a viable way to adjust the amount of fueling for the enrichment process, there was a noticeable issue with the breakpoint data (input vector). The first two seconds of engine combustion required a more dynamic fuel enrichment profile than initially hypothesized. A greater ability to control interpolation between breakpoints in the look-up tables was needed. To address this issue, more resolution was added to the first two seconds of the look-up table’s values by simply be dividing the two seconds into quarter-seconds, as shown in Figure 5.9.

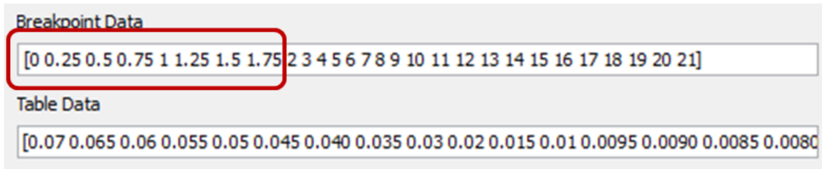


Figure 5.9: Higher Resolution for Look-up Tables

Another issue with the initial fuel enrichment logic was that the enrichment was disabled based on a timer rather than by the actual response of the system. A justifiable way to control the disabling of enrichment was to link it to the response of the post-catalyst EGO sensor. The post-catalyst EGO sensor allows the controller to know when the stored oxygen from the catalyst has been used and what type, if any, emissions breakthrough is taking place.

The post-catalyst EGO sensor was therefore used to indicate when the oxygen supply was diminishing; essentially giving the controller an advanced warning that enrichment would need to be disabled. Since the post-catalyst EGO sensor starts at a zero value when the engine is initially fired, a value of 0.1 was chosen to disable the open-loop fuel spike.

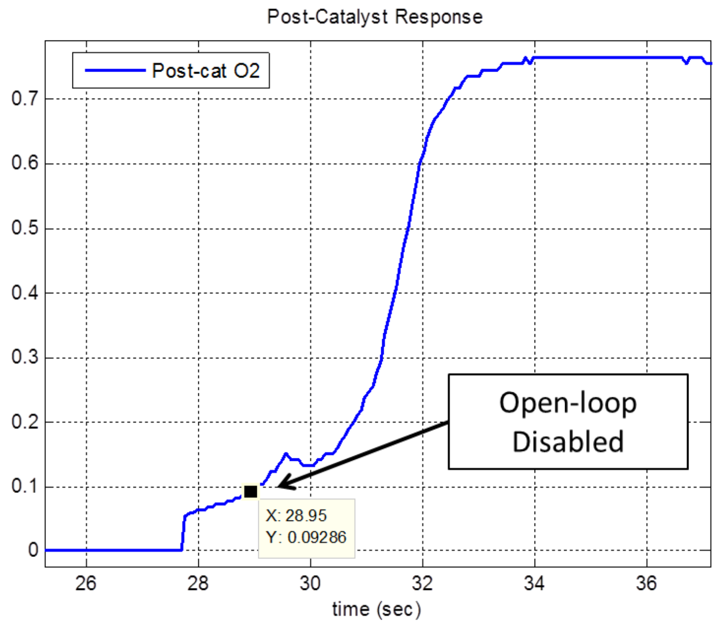


Figure 5.10: Open-loop Disable Value

The value of 0.1 from a rising post-catalyst EGO sensor was a good indication that the initial fuel spike had worked properly and that oxygen was starting to be used in the catalyst; however, it did not guarantee that the catalyst would eventually be conditioned correctly to reach its stoichiometric set point. To ensure that there is controlled enrichment that will use up more oxygen from the catalyst, closed-loop fuel enrichment logic was developed.

The closed-loop fuel enrichment becomes enabled immediately when the open-loop is disabled. The logic uses the feedback fueling logic already implemented in the main engine control model, but instead commands a higher desired equivalence ratio (EQR). The cold start engine condition requires an EQR of 1.03 while the warm and hot starts require 1.02. The closed-loop control causes the ECM to maintain rich engine combustion until the post-catalyst EGO sensors gives a reading at the second threshold, 0.55. This value was chosen because of the steep slope of the sensor reading at 0.55 in Figure 5.11. Disabling all enrichment at this point allows the catalyst to stop using stored oxygen and run close to its stoichiometric set point, rather than overshooting and using up all the oxygen, causing rich emission breakthrough.

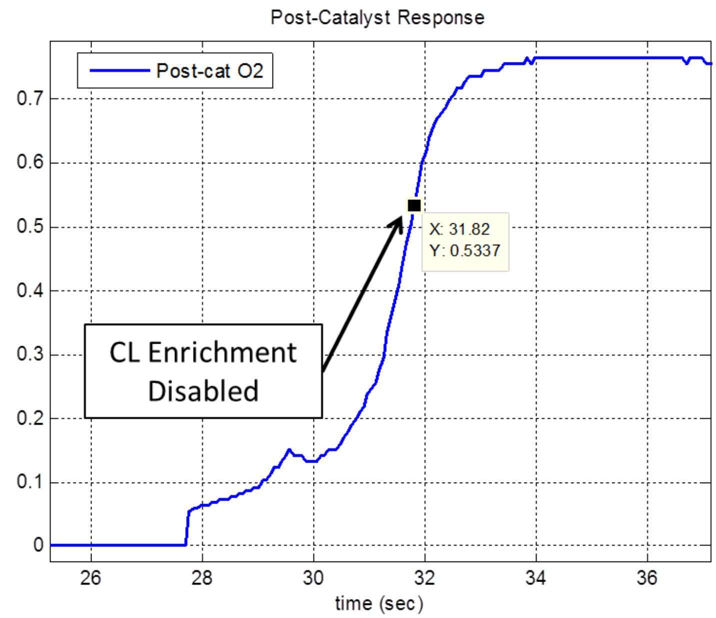


Figure 5.11: Closed-loop Disable Value

After the closed-loop enrichment is disabled by the logic, the closed-loop non-enrichment controls the EQR ratio of the engine and normal, steady-state operation resumes. Logic is in place to prevent enrichment from re-enabling should the post-catalyst EGO sensor signal fall below the threshold values. The logic will only reset and allow any enrichment to occur when the injectors are disabled.

5.4 Calibration

With all the modifications to the control software in place, testing was resumed at the same operating conditions. In the same manner that the initial testing and calibration was conducted, the results of each test were analyzed and modifications to the look-up table values were made to adjust the magnitude and duration of the initial fuel spike. It was desirable to have an initial fuel spike that got a quick post-catalyst EGO response that rose above the first threshold to turn off open-loop enrichment. Beyond this point, the fuel spike was not needed and closed-loop enrichment would condition the catalyst.

An example of how the fuel spike was calibrated for each engine temperature range, a warm start is shown in Figures 5.12 and 5.13.

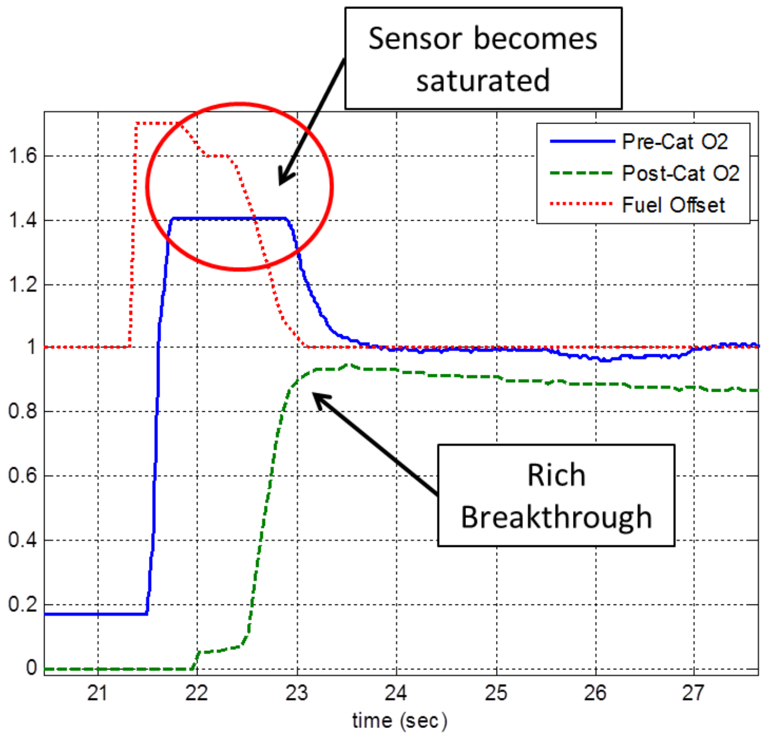


Figure 5.12: Warm Test - High Spike

Table 5.2: Warm Test (High Spike) – Look-up Table Values

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00
Offset	0.70	0.70	0.65	0.60	0.60	0.40	0.20	0.10	0.00	0.00	0.00

The fuel spike shown in Figure 5.12 was undesirable because it caused too much enrichment. The post-catalyst EGO signal ramped up to the rich side and stayed there, indicating rich emission breakthrough. The spike also caused so much fuel to be injected, that the pre-catalyst EQR sensor hit its saturation limit at 1.4.

Calibrating the look-up table to achieve a smaller, longer fuel spike resulted in a more desirable pre- and post-catalyst sensor response. In Figure 5.13, the lowered spike results in a slower post-catalyst response that does not indicate either lean or rich emission breakthrough. The difference in fueling profiles (from Tables 5.2 and 5.3) is shown in Figure 5.14.

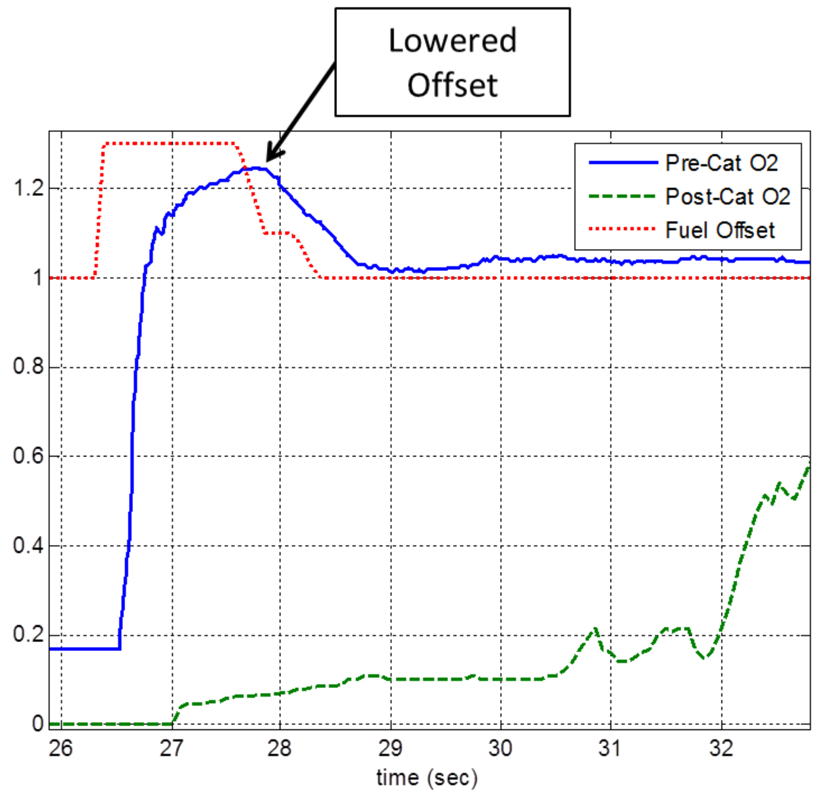


Figure 5.13: Warm Test - Lowered Spike

Table 5.3: Warm Test (Lowered Spike) - Look-up Table Values

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00
Offset	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.10	0.10	0.00	0.00

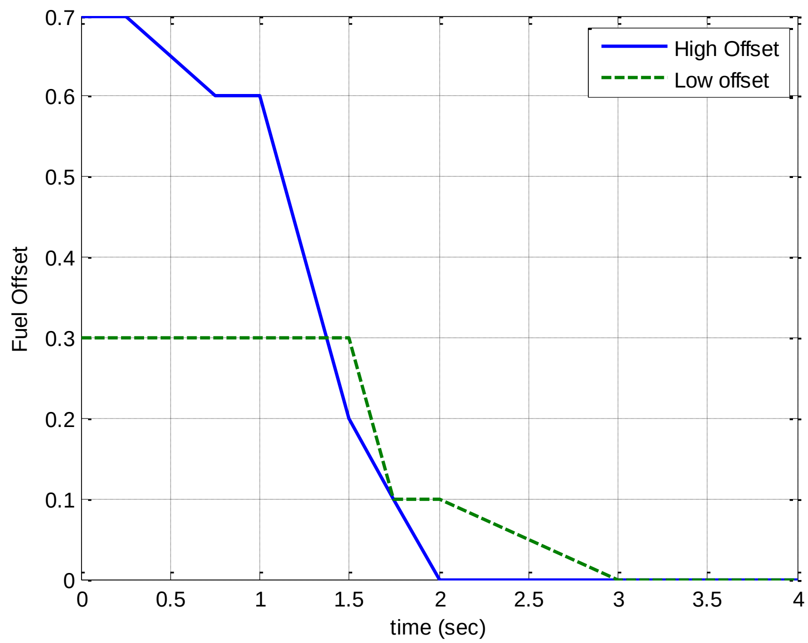


Figure 5.14: Fuel Profiles - Avoiding Sensor Saturation

After the high-level issues with the fuel enrichment profiles were resolved by calibration of the look-up tables, refinement specific to certain areas in the profile was attempted. One of the areas includes optimizing the amount of fuel needed in the spike to achieve the initial rise in the post-catalyst EGO sensor. Figure 5.15 shows a pre-catalyst EQR response to the corresponding look-up table values in Table 5.4 and Figure 5.16.

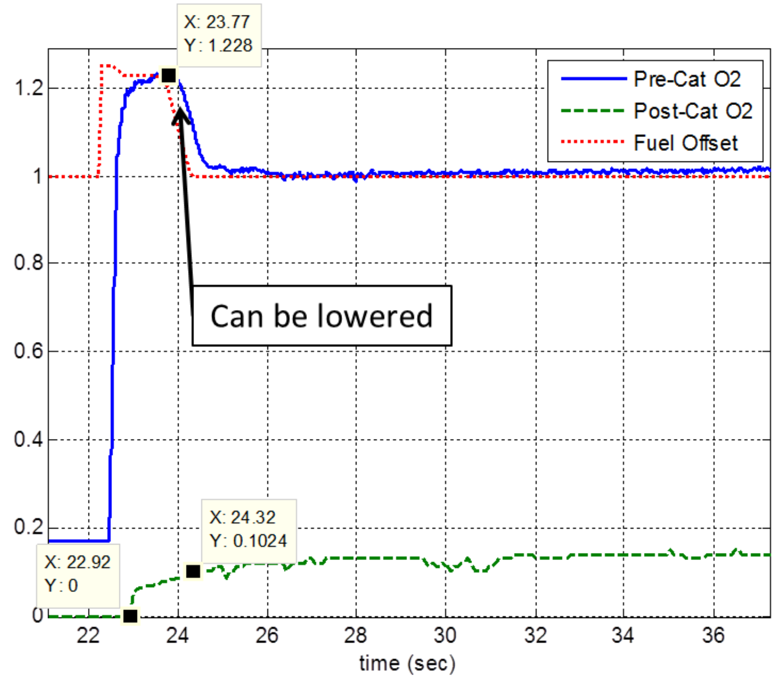


Figure 5.15: Hot Test - High Offset

Table 5.4: Hot Test (High Offset) - Look-up Table Values

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00
Offset	0.25	0.25	0.23	0.23	0.23	0.23	0.20	0.10	0.00	0.00	0.00

The offset shown in Figure 5.15 was lowered slightly for the hot operating condition and the post-catalyst EGO response still rose to the closed-loop enrichment threshold within a comparable amount of time, as shown in Figure 5.16. The change in fuel offset profiles is shown in Figure 5.17.

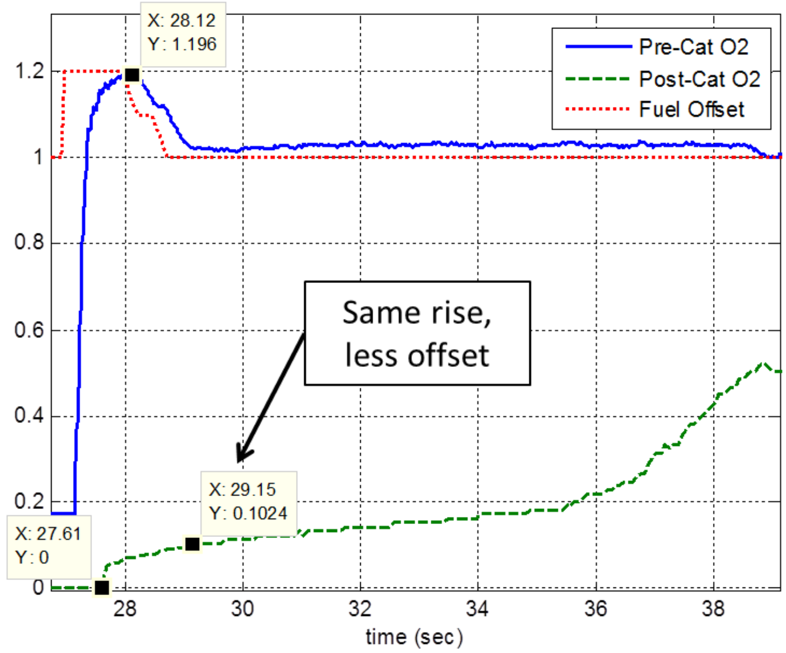


Figure 5.16: Hot Test - Lower Offset

Table 5.5: Hot Test (Lower Offset) - Look-up Table Values

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00
Offset	0.20	0.20	0.20	0.20	0.20	0.10	0.10	0.00	0.00	0.00	0.00

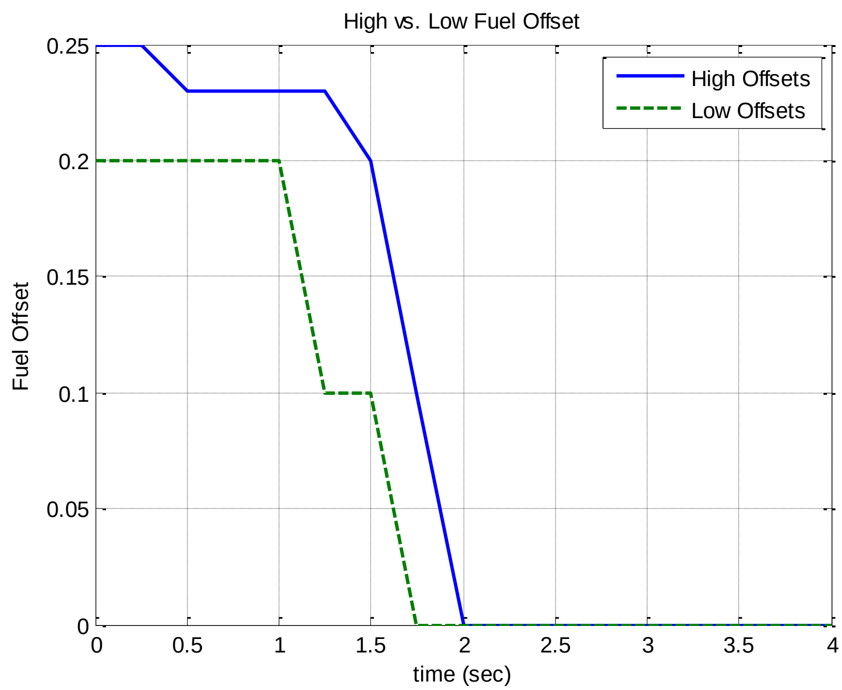


Figure 5.17: High vs. Low Fuel Offset

Another area of interest was optimizing the amount of enrichment used when closed-loop control became enabled. This steady amount of enrichment caused an increase or decrease in the speed of the catalyst response. The effect of this enrichment value on a hot startup event is captured in Figures 5.18 and 5.19. In Figure 5.18, the closed-loop desired EQR was set to 1.02. The post-catalyst EGO sensor signal rose to the second threshold value (0.55) within about 4.82 seconds after reaching the first threshold value (0.1). An item to make note of in the plot of pre-catalyst EQR response is that it briefly dips down to around stoichiometry before climbing back to the desired EQR of 1.02. This was caused by the look-up table values changing from a non-zero number to zero. The controller responded slowly to the sudden change to a leaner EQR, but eventually recovered. This caused the post-catalyst EGO rise to be delayed slightly, but the main concept behind the calibration of the desired EQR can still be observed.

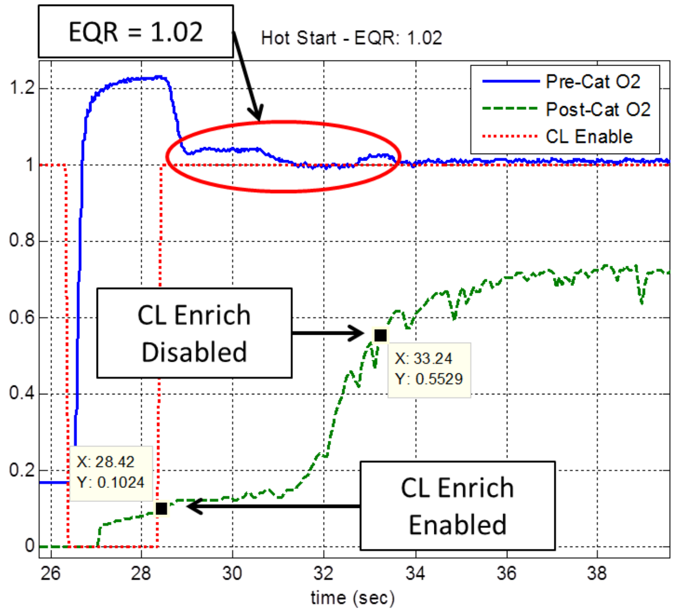


Figure 5.18: Catalyst Response - EQR = 1.02

The experiment was run again with the same look-up table values for the fuel spike and the same engine conditions. The only change was an increase of desired EQR to 1.03 for the closed-loop fuel enrichment. As seen in Figure 5.19, the post-catalyst EGO sensor responded faster and rose to the second threshold in approximately 3.01 seconds after the first threshold was achieved. This faster response allowed regular closed-loop control to be enabled sooner and normal steady-state engine operation to start.

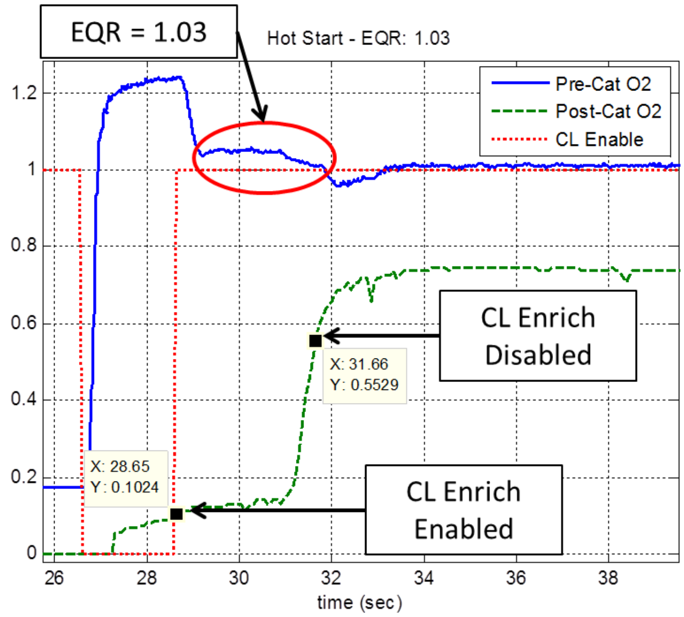


Figure 5.19: Catalyst Response - EQR = 1.03

Software calibration continued for each cold, warm, and hot engine operating ranges until desirable results were collected and the control logic proved to be robust enough to replicate results after multiple tests.

The catalyst response that resulted from the calibrated fuel enrichment control algorithm was promising for all engine temperature ranges. The software was able to appropriately command the proper amount of fuel enrichment on startup events that effectively conditioned the catalyst.

6.1 Experimental Results – Warm Condition

The two important areas that were considered for determining whether or not the software was properly calibrated were the catalyst response and the torque response of the engine. These final results for the warm engine temperature condition (40-70 °C) are shown in Figures 6.1, 6.2, and 6.3.

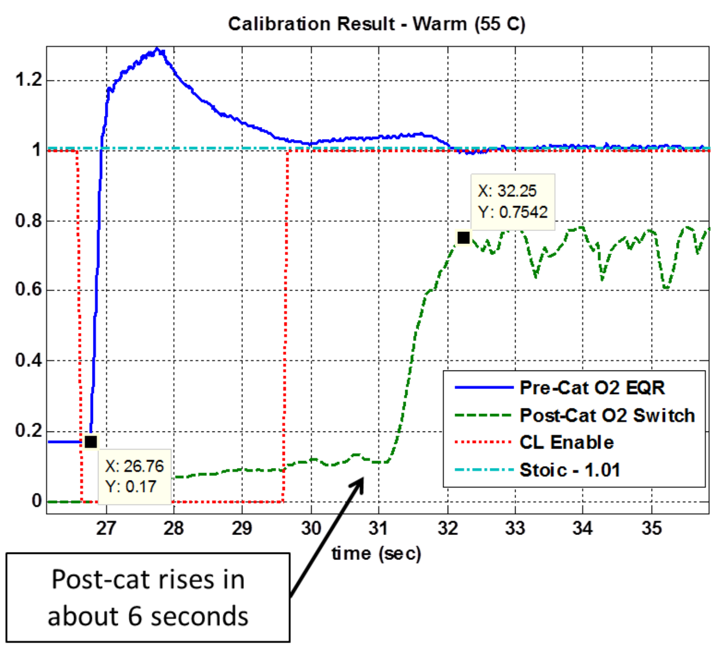


Figure 6.1: Final Catalyst Response - Warm (55 C)

An excellent catalyst response is shown in Figure 6.1. With the high commanded fueling in the fuel spike, the post-catalyst EGO signal passes the first threshold within approximately 2.5 seconds after injectors are enabled. Closed-loop enrichment is effectively used after that point and the rich combustion emissions use a significant amount stored oxygen from the catalyst. This results in the post-catalyst EGO signal rising to its stoichiometric set point within about 6 seconds of enabling fuel injectors. The post-catalyst signal does not overshoot the stoichiometric set point and holds relatively steady around the set point after closed-loop enrichment is disabled. This indicates that the catalyst was properly conditioned and that the correct amount of oxygen was used during the startup event to avoid both lean and rich emission breakthrough. When placed next to the baseline catalyst response, as in Figure 6.2, the improvements to catalyst conditioning and avoidance of emission breakthrough is very evident.

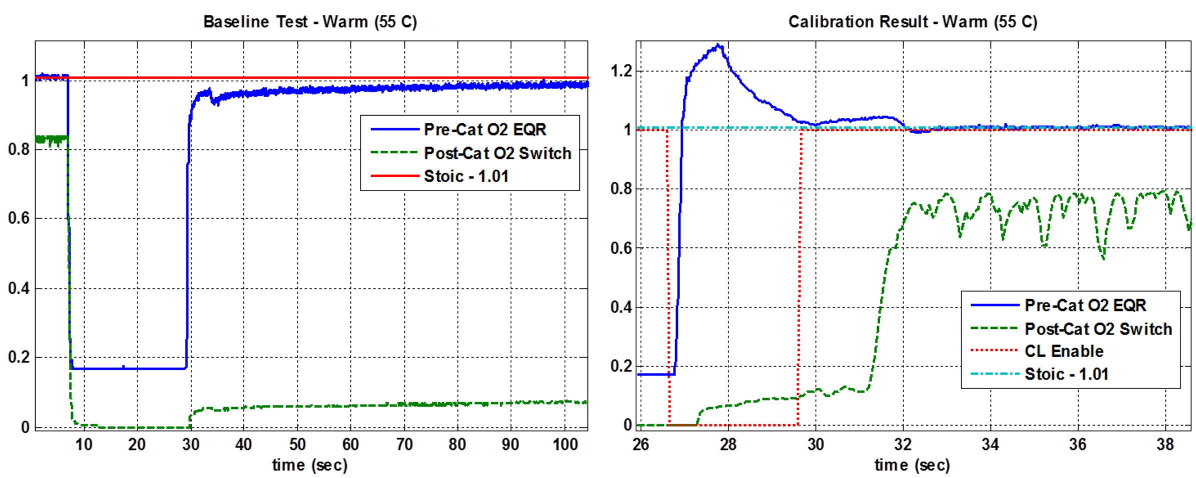


Figure 6.2a: Baseline Catalyst Response (Warm) **Figure 6.2b: Final Catalyst Response (Warm)**

Figure 6.2: Comparison of Final Catalyst Results - Warm (55 C)

Figure 6.1 also shows the smooth transition between the fuel spike, the closed-loop fuel enrichment, and the normal closed-loop control for pre-catalyst EQR. Having smooth transitions, while not essential to the goals of this research project, means that the engine will have a more refined operation and the torque produced by engine should be nearly constant. The torque in Figure 6.3 appears to be slightly noisy, but that is due to limitations of filtering that could be applied to the signal in the dynamometer controller.

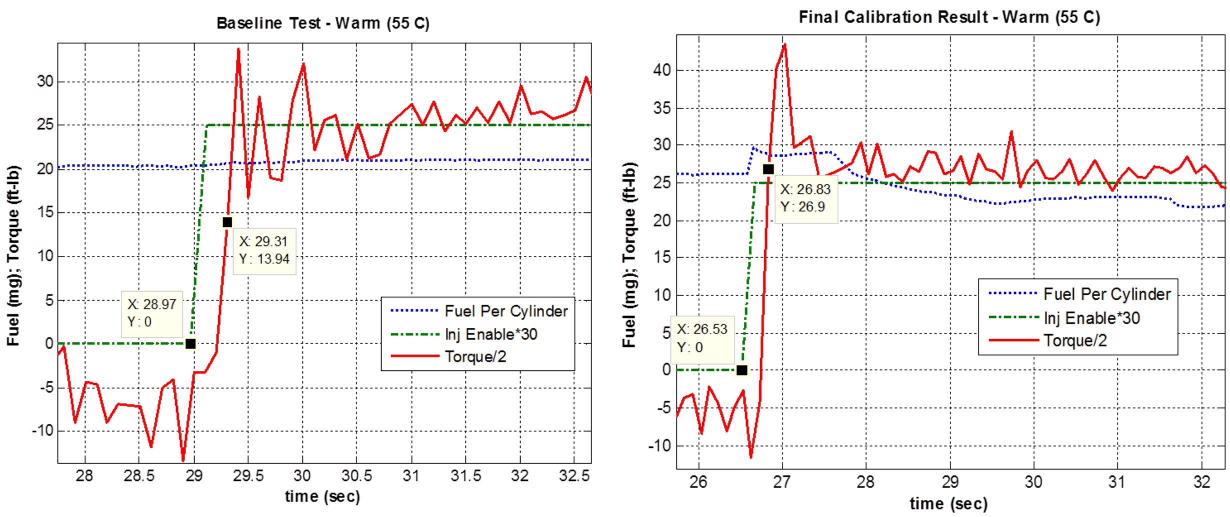


Figure 6.3a: Baseline Torque Response (Warm) **Figure 6.3b: Final Torque Response (Warm)**

Figure 6.3: Comparison of Final Torque Results - Warm (55 C)

The time that it takes to produce the desired torque after injectors were enabled for the calibration result in Figure 6.3b shows a slight decrease of about 0.04 seconds. The torque response was not that affected by the fuel enrichment because of the how well the fuel can evaporate within the intake ports when the block temperature is warm or hot. Because of this, the only major difference in torque response was expected from the cold engine condition.

The final values for the warm look-up table are given in Table 6.1. The final values for the closed-loop enrichment parameters including desired EQR, the closed-loop enable threshold, and the closed-loop disabled threshold are shown in Table 6.2 and Figure 6.4.

Table 6.1: Calibrated Look-up Table Values - Warm

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00	5.00	6.00	7.00
Offset	0.40	0.30	0.30	0.30	0.30	0.17	0.13	0.10	0.08	0.00	0.00	0.00	0.00	0.00

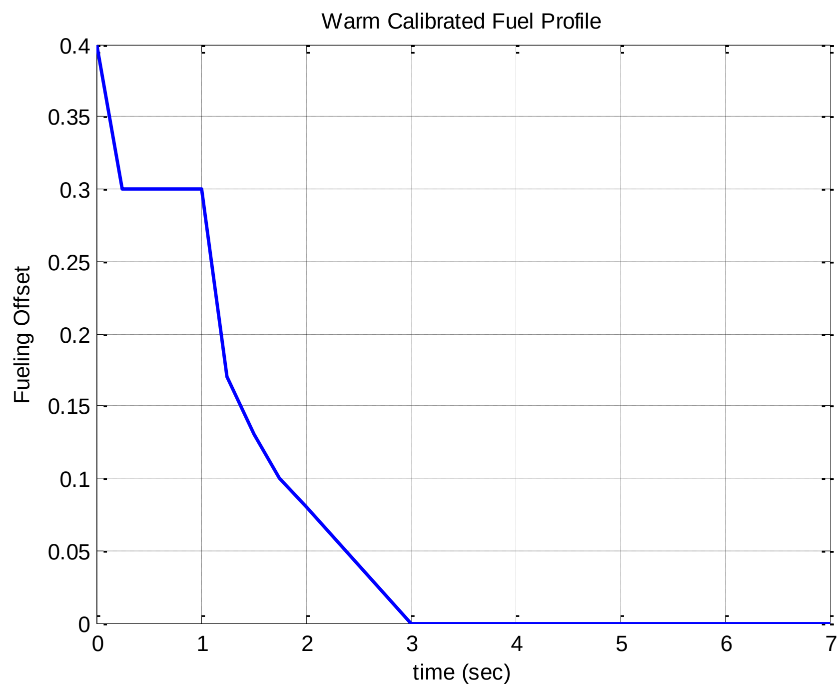


Figure 6.4: Calibrated Look-up Table Values – Warm

Table 6.2: Calibrated Closed-loop Enrichment Parameters - Warm

Desired EQR	1.03
CL Enable	0.10
CL Disable	0.55

6.2 Experimental Results – Hot Condition

As with the warm experimental results, the catalyst response and torque response are of interest for determining if the calibrated software functions as desired for hot engine conditions (ETC > 70 °C). These are found in Figures 6.5, 6.6, and 6.7.

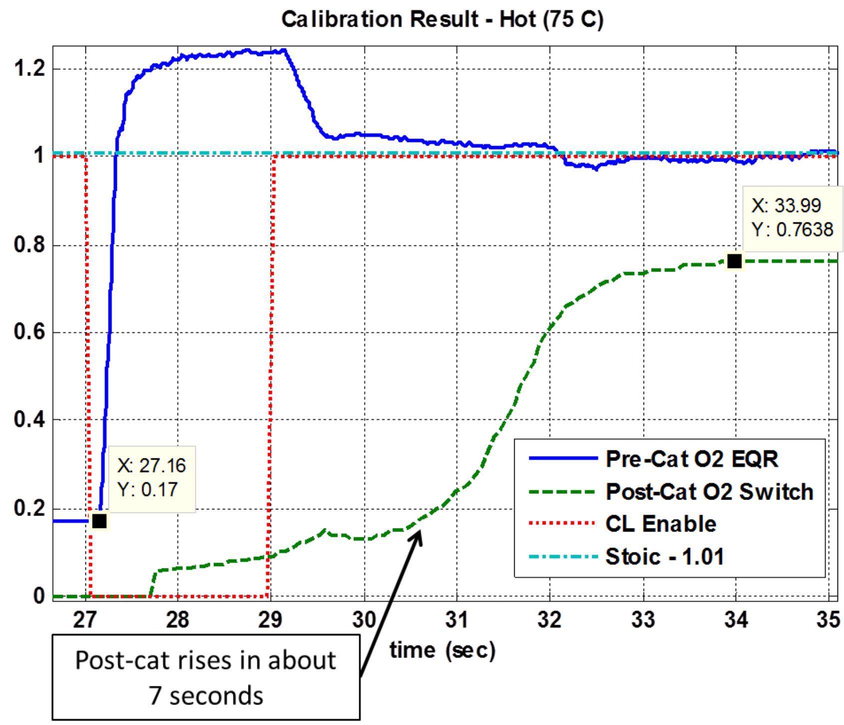


Figure 6.5: Final Catalyst Response - Hot

Similar to the warm results, the catalyst response for the hot engine condition is a very desirable result. The initial fuel caused the post-catalyst EGO sensor signal to surpass the first threshold for closed-loop enrichment in approximately 2 seconds after injectors were enabled. The closed-loop control was maintained until the second threshold was achieved and the enrichment turned off. This occurred about 7 seconds after the injectors were enabled. As with the warm response, the hot response does not overshoot the post-catalyst stoichiometric value and the signal stays around that set point after enrichment is disabled. Therefore, the catalyst was properly conditioned and the avoidance of both lean and rich emission breakthrough was achieved. The comparison to the baseline results from the hot condition is shown in Figure 6.6.

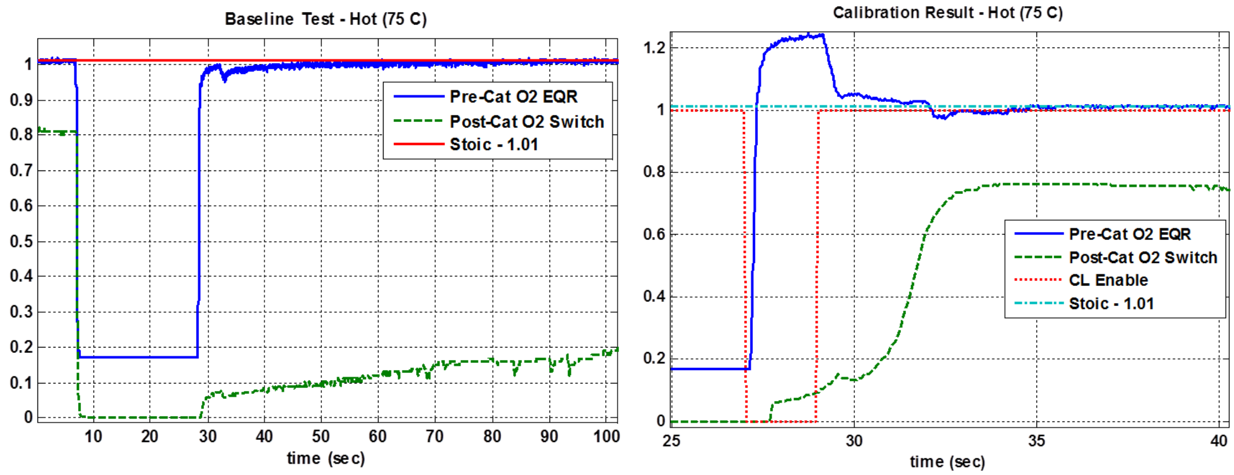
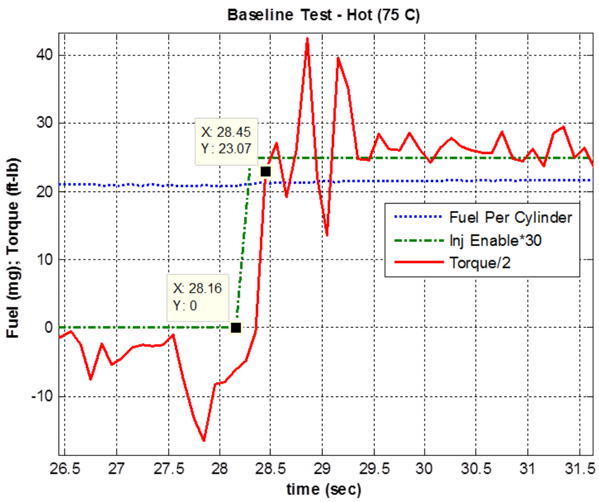


Figure 6.6a: Baseline Catalyst Response (Hot) **Figure 6.6b: Final Catalyst Response (Hot)**

Figure 6.6: Comparison of Final Catalyst Results – Hot (75 C)

The torque response of the calibrated software for the hot conditions, shown in Figure 6.7, is very similar to the warm calibration results. There is a slight decrease in the time it takes to achieve the desired torque from when the injectors are enabled (approximately 0.01 seconds). However, as with the warm case, the fuel is able to evaporate very quickly whenever the fuel-air mixture enters the cylinder and fuel enrichment has little effect in this situation.



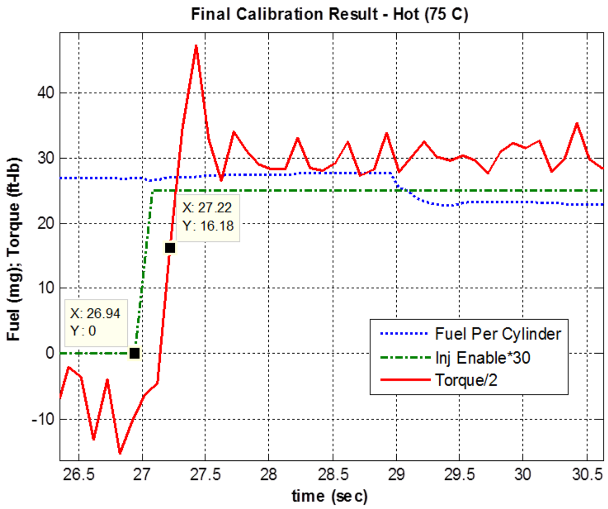


Figure 6.7a: Baseline Torque Response (Hot) **Figure 6.7b: Final Torque Response (Hot)**

Figure 6.7: Comparison of Final Torque Results – Hot (75 C)

The final values of the hot look-up table used in the calibrated software are found in Table 6.3, and the final values for the closed-loop enrichment parameters are given in Table 6.4 and Figure 6.8.

Table 6.3: Calibrated Look-up Table Values - Hot

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00	5.00	6.00	7.00
Offset	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.15	0.10	0.05	0.00

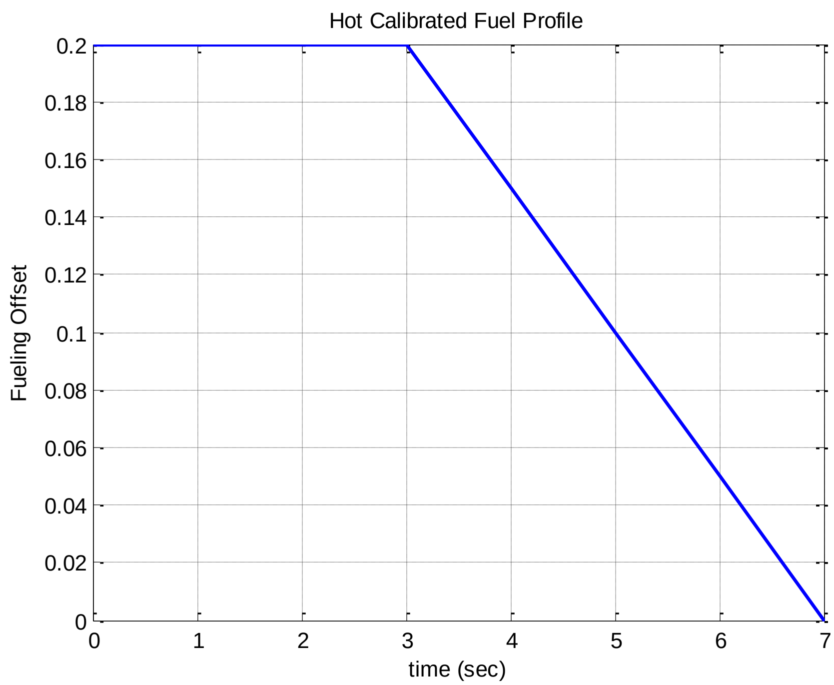


Figure 6.8: Calibrated Look-up Table Values – Hot

Table 6.4: Calibrated Closed-loop Enrichment Parameters - Hot

Desired EQR	1.03
CL Enable	0.10
CL Disable	0.55

6.3 Experimental Results – Cold Condition

The catalyst used in the dynamometer during testing had an electrically heated catalyst (EHC) contained within the canister; however, the EHC was never connected to a power circuit and was not used for pre-heating the catalyst for cold startup events. Because of this, the catalyst was cold and below light-off temperature when the engine began firing. A cold catalyst reacts in an unstable manner compared to a hot catalyst, so calibration work could not be completed for cold startup fuel enrichment.

Even though no calibration could be finalized, improvements were still made to the startup based on what was observed from warm and hot startups. The baseline tests for cold start showed very poor responses of the catalyst and of the engine torque. In the same manner as the warm and hot calibration, adjustments were made to the look-up table values and the closed-loop fuel enrichment parameters until acceptable results were achieved.

The response of the catalyst to the limited calibration work is shown in Figure 6.9. The initial fuel spike successfully caused the pre-catalyst EQR to reach stoichiometry, something that was never achieved in the baseline test. While the catalyst itself is in an unstable state at initial firing because of the low temperature, it becomes more stable as it gets hotter from the exhaust gas heat transfer to the substrate. Because of this, the post-catalyst EGO sensor began responding after a few seconds, though the signal was still unstable. The sudden rises seen in Figure 6.9 indicate that there is some catalyst conditioning occurring and that some of the stored oxygen is being depleted. The response is still too unstable to determine precisely if lean or rich emission breakthrough is occurring, but it can be inferred that lean breakthrough is being avoided. This is justified by the fact that the combustion never goes lean during the startup event after the EQR initially ramps up to stoichiometry.

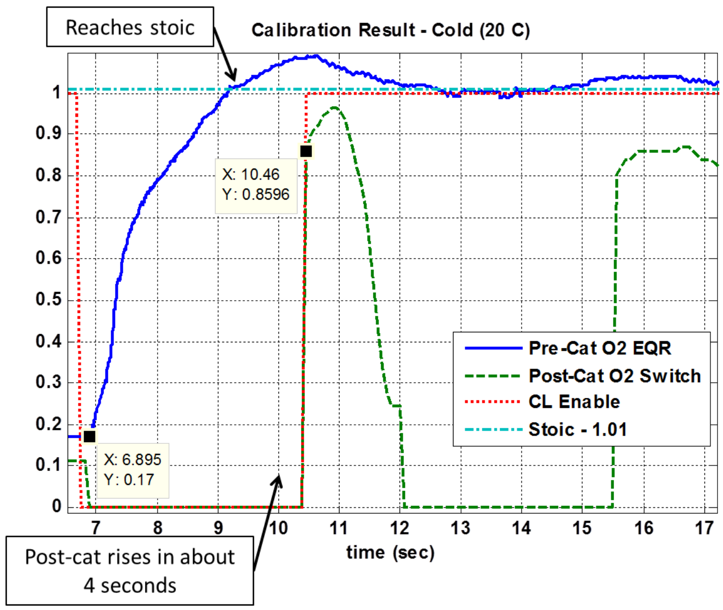


Figure 6.9: Final Catalyst Response - Cold (20 C)

When compared to the baseline test results in Figure 6.10, the differences in catalyst response are very evident. The baseline EQR response never reached stoichiometry in over 70 seconds of firing, where the new logic was able to reach stoichiometry in approximately 2.5 seconds after injectors were enabled.

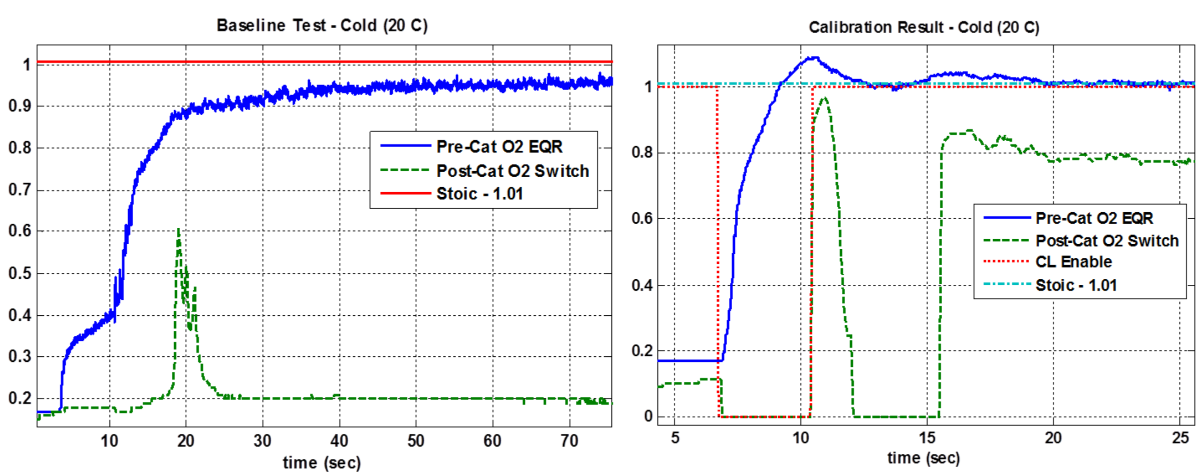


Figure 6.10a: Baseline Catalyst Response (Cold) **Figure 6.10b: Final Catalyst Response (Cold)**

Figure 6.10: Comparison of Final Catalyst Results – Cold (20 C)

Unlike the calibration results for warm and hot startup, the cold torque response from the new fuel enrichment software is comparably improved over the baseline. As graphed in Figure 6.11, the baseline test took approximately 9 seconds from injector enable to begin producing consistently positive torque. It took an additional 4 seconds to reach the desired torque, causing a total of 13 seconds of delay in the system. The new torque response began producing positive torque in about 0.75 seconds, nearly 8.5 seconds faster than the baseline. From there, it took the engine approximately an additional 0.5 seconds to reach the desired torque value. These results indicate a dramatic improvement in torque response for cold start with fuel enrichment.

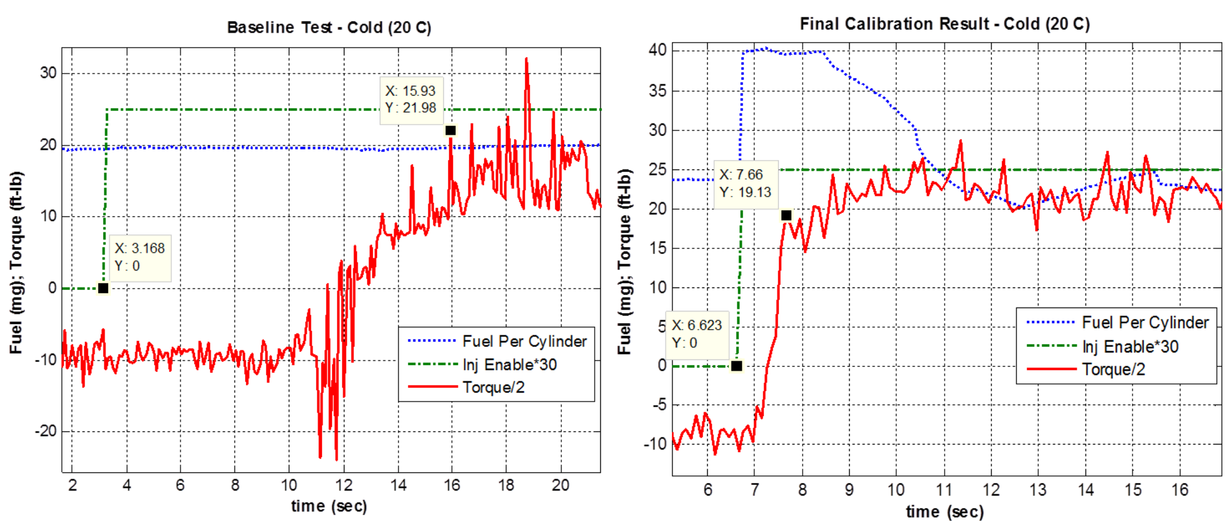


Figure 6.11a: Baseline Torque Response (Cold) **Figure 6.11b: Final Torque Response (Cold)**

Figure 6.11: Comparison of Final Torque Results – Cold (20 C)

Table 6.5 and Figure 6.12 contain the final values of the cold look-up table. The values for the closed-loop enrichment parameters are also given in Table 6.6. Unlike the warm and hot cases, the first post-catalyst EGO sensor threshold that is used to enable closed-loop enrichment was set at 0.25. This adjustment was needed because the post-catalyst EGO sensor consistently had an offset reading of 0.15-0.2 during engine motoring before firing began on cold starts. This was likely caused by the sensor not initially being warm.

Table 6.5: Calibrated Look-up Table Values - Cold

Time (s)	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	3.00	4.00	5.00	6.00	7.00
Offset	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.70	0.40	0.20	0.00	0.00

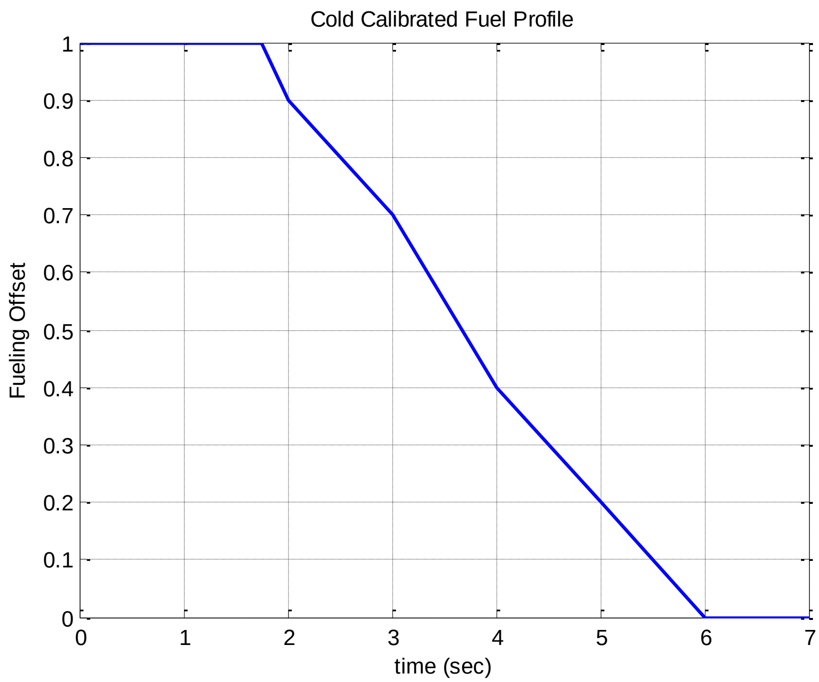


Figure 6.12: Calibrated Look-up Table Values – Cold

Table 6.6: Calibrated Closed-loop Enrichment Parameters - Cold

Desired EQR	1.05
CL Enable	0.25
CL Disable	0.55

6.4 Experimental Results – Summary

The results showed some amount of improvement in the decrease of post-catalyst and torque responses. These findings are summarized in the figures and tables below.

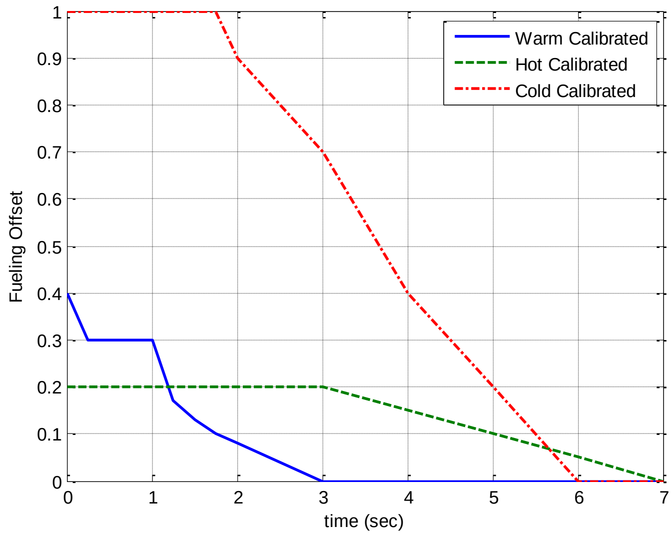


Figure 6.13: Final Calibrated Fuel Profiles

Figure 6.13 shows the fueling offset profiles given by the look-up table values for all three engine startup conditions. The cold start offsets are clearly much greater than the warm or hot. This is due to building the fuel film in the intake ports before torque can be produced.

Table 6.7 shows all important calibratable parameters that were used during the testing process and shows the initial and final response times of the system. The initial response time for the post-catalyst EGO sensor was longer than 70 seconds, as shown in Figures 4.1, 3, and 5. Therefore, the times are listed in this table as 70+ seconds. Figures 6.14 and 6.15 graphically show the differences between initial and final torque production responses and initial and final catalyst responses.

Table 6.7: Overall Results Table

	Cold	Warm	Hot
Desired EQR	1.05	1.03	1.03
CL Enable (post-cat)	0.25	0.10	0.10
CL Disable (post-cat)	0.55	0.55	0.55
Torque Production - Initial (sec)	12.76	0.34	0.29
Torque Production - Calibration (sec)	1.04	0.30	0.28
Catalyst Response - Initial (sec)	70+	70+	70+
Catalyst Response - Calibration (sec)	3.57	5.49	6.83

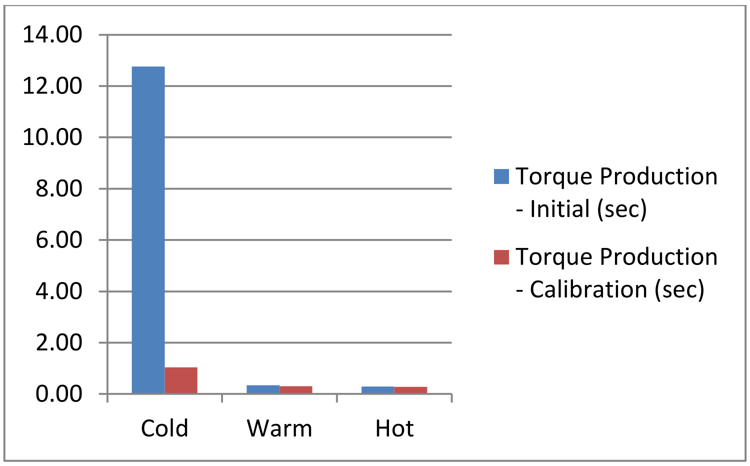


Figure 6.14: Initial vs. Final Torque Response

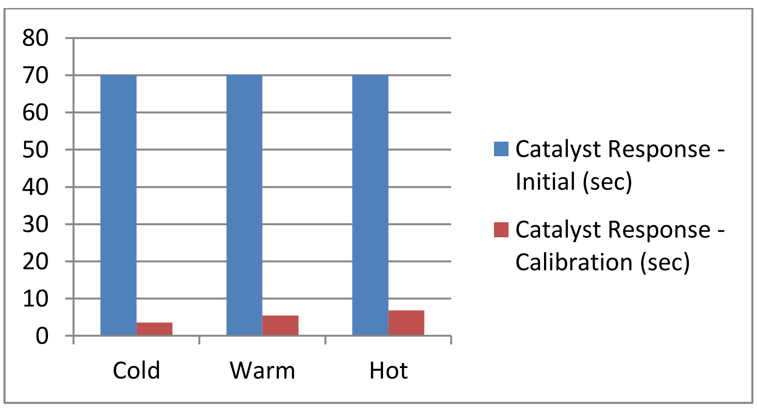


Figure 6.15: Initial vs. Final Catalyst Response

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

The development of control software to condition the catalytic converter and reduce spikes in tailpipe emissions released during stop/start events was completed. Baseline data was collected with no fuel enrichment and analyzed to determine where improvements to the startup fueling profile could be made. Based off of this analysis, new control logic was created and implemented into the main engine control model and flashed onto the rapid-prototyping engine control module. Initial testing and calibration took placed based off of the analysis of each experiment ran in the dynamometer test cell. Within the calibration work arose a point where the fueling profile could not effectively be made to better suit what was needed using the developed software. At this point, additional logic was created and implemented to allow for finer calibration of the fuel enrichment profile and a more robust control method. This logic was then calibrated until desirable catalyst and torque responses were achieved for cold, warm, and hot engine operating conditions.

The results from testing the calibrated software are conclusive for the warm and hot engine conditions. The fuel enrichment logic used effectively conditioned the catalyst by depleting the amount of stored oxygen and reducing the occurrence of lean emissions bypass without causing rich emissions bypass. The calibrated startup fueling profile did shorten the amount of time for torque to be produced; however, these time differences were very small and negligible. The software for warm and hot stop/start is also robust enough that it could be implemented on the EcoCAR vehicle for use in the hybrid powertrain.

The results for cold engine startup must be classified as inconclusive because the calibration work was not completed. The cold catalyst was too unstable for properly developing robust software that would meet the project goals and be able to be used in the EcoCAR vehicle. However, improvements were made to catalyst and torque responses for cold startup. The software was able to have the engine combustion achieve stoichiometry within a short amount of time and the time taken to produce positive torque was decreased by approximately 94%.

7.2 Future Work

To conclude the stop/start emission reduction research, the cold startup logic needs to be properly calibrated. This can be done by either setting up a driver circuit to deliver power to the electrically-heated catalyst in the dynamometer test cell or by conducting tests in the EcoCAR vehicle, which will have the driver circuit already set up and functional by the year two competition. The electrically heated catalyst can then be used to pre-heat the main catalyst substrate to light-off temperature before the engine is started. This will cause the catalyst response to be stable and will replicate the cold startup condition that will actually be occurring in the vehicle. The software can be calibrated in the same manner that it was for warm and cold stop/starts in this research project.

Even though desired system responses were achieved from the calibration work conducted for this thesis, the calibrations can be tuned even further by actually measuring the amount of emissions being release and ensuring that little to no NO_x is bypassing the catalyst. This can be done by using the Horiba MEXA 7500 emissions analyzer that is already on location in the dynamometer test cell used for this research. This exhaust gas analyzer can be used to precisely measure the amount of emissions being released and ensure that everything is within the EcoCAR competition requirements and the OSU EcoCAR team goals.

The OSU EcoCAR team is installing heated fuel injectors (HFIs) during spring semester 2013. The HFIs will heat the E-85 as it is being injected into the intake runners. These will undoubtedly change the fuel dynamics during startup events as the fuel will either be vaporized as it’s being sprayed in or will be able to easily evaporate within the intake ports. Tests will need to be conducted and adjustments made to the fuel enrichment profiles for cold, warm, and hot startups.

The final item that needs to be completed with this research is the implementation of the fuel enrichment software onto the vehicle. The software will need to be modified so that certain parameters are selected or commanded automatically, rather than with a manual input that was sufficient for testing in a dynamometer test cell. The code will also need to be tested for any faults and the robustness validated before it is loaded onto the vehicle for everyday use.

CHAPTER 8: BIBLIOGRAPHY

[1] Bishop, J., Nedungadi, A., Ostrowski, G., Surampudi, B., Armiroli, P., & Taspinar, E. (2007). An Engine Start/Stop System for Improved Fuel Economy. *2007 SAE World Congress*. Detroit: SAE International.

[2] Bezaire, B. A. (2011). *Modeling and Control of an Electrically-Heated Catalyst*. Columbus: The Ohio State University, M.S. Thesis.

[3] Bovee, K. M. (2010). *Development of Controller for the Post-Catalyst Oxygen Sensor on EcoCAR Vehicle*. Columbus: The Ohio State University, Undergraduate Honors Thesis.

[4] Chevalier, A., Vigild, W. C., & Hendricks, E. (2000). Predicting the Port Air Mass Flow of SI Engines in Air/Fuel Ratio Control Applications. *2000 SAE World Congress*. Detroit: SAE International.

[5] Everett, R. V. (2010). *Transient Air Dynamics Modeling for an Advanced Alternative Fueled Engine*. Columbus: The Ohio State University, Undergraduate Honors Thesis.

[6] Inoue, T., & Oi, Y. (2004). *U.S. Patent No. 6,742,327*. Washington, DC: U.S.

[7] Khossusi, T., McCullough, G., & Douglas, R. (2004). Investigation of Oxygen Storage in Three Way Automotive Catalysts. *Fuels & Lubricants Meeting & Exhibition*. Toulouse: SAE International.

[8] Midlam-Mohler, S. (2006). *U.S. Patent No. 7,051,514*. Washington, DC: U.S.

[9] Midlam-Mohler, S. (2007). *U.S. Patent No. 7,257,943*. Washington, DC: U.S.

[10] Muske, K. R., & Peyton Jones, J. C. (2006). Multi-objective model-based control for an automotive catalyst. *Journal of Process Control*, 16, 27-35.

[11] Muske, K. R., Peyton Jones, J. C. & Howse, J. W. (2008) A model-based approach to automotive three-way catalyst on-board monitoring. *Journal of Process Control*, 18, 163-172.

[12] Theis, J. R. (1996). An Engine Test to Measure the Oxygen Storage Capacity of a Catalyst. *International Fall Fuels & Lubricants Meeting & Exposition*. San Antonio: SAE International.

[13] Theis, J. R., LaBarge, & W. J., Fisher, G. B. (1993). The Effects of Catalyst Volume and Ceria Content on the Emission Performance and Oxygen Storage Capacity of Automotive Catalysts. *Fuels and Lubricants Meeting and Exposition*. Philadelphia: SAE International.

[14] Watanabe, O., Nakajima, S., Goto, H., & Matsunaga, T. (2007). Development of CNG Engine with Variable Valve Timing Electronic Control. *14th Asia Pacific Automotive Engineering Conference*. Hollywood, CA: SAE International.

APPENDIX

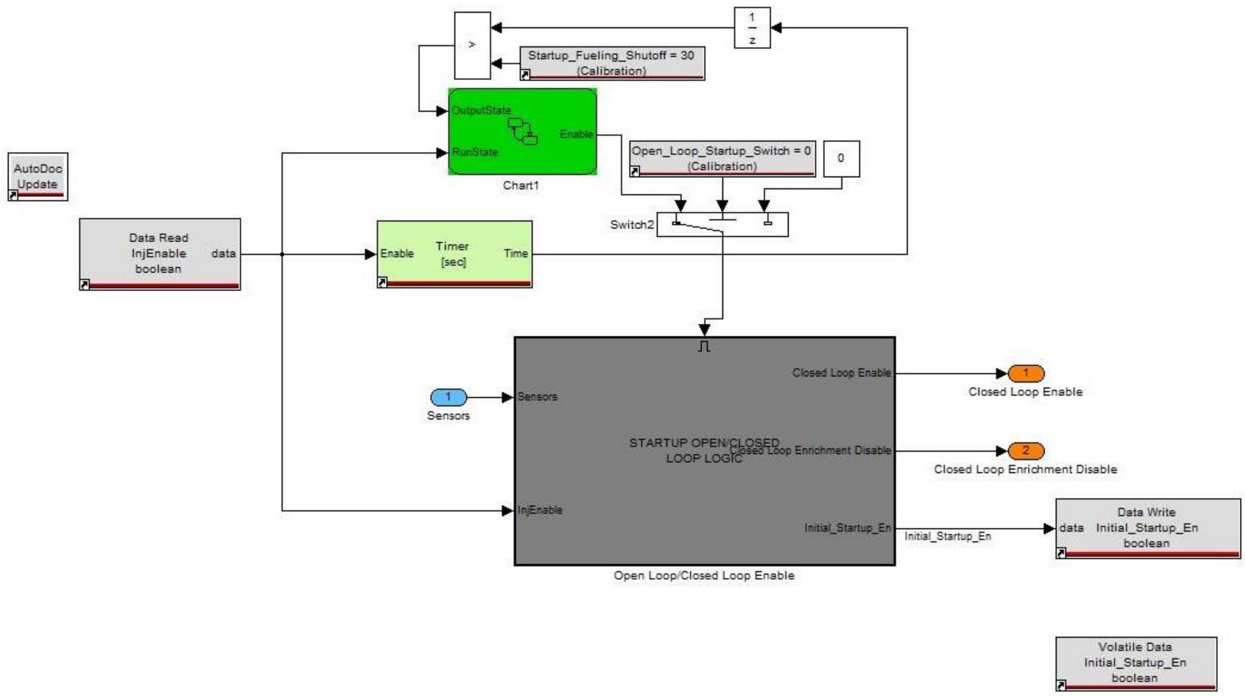


Figure A1: Startup Closed-loop Threshold Logic

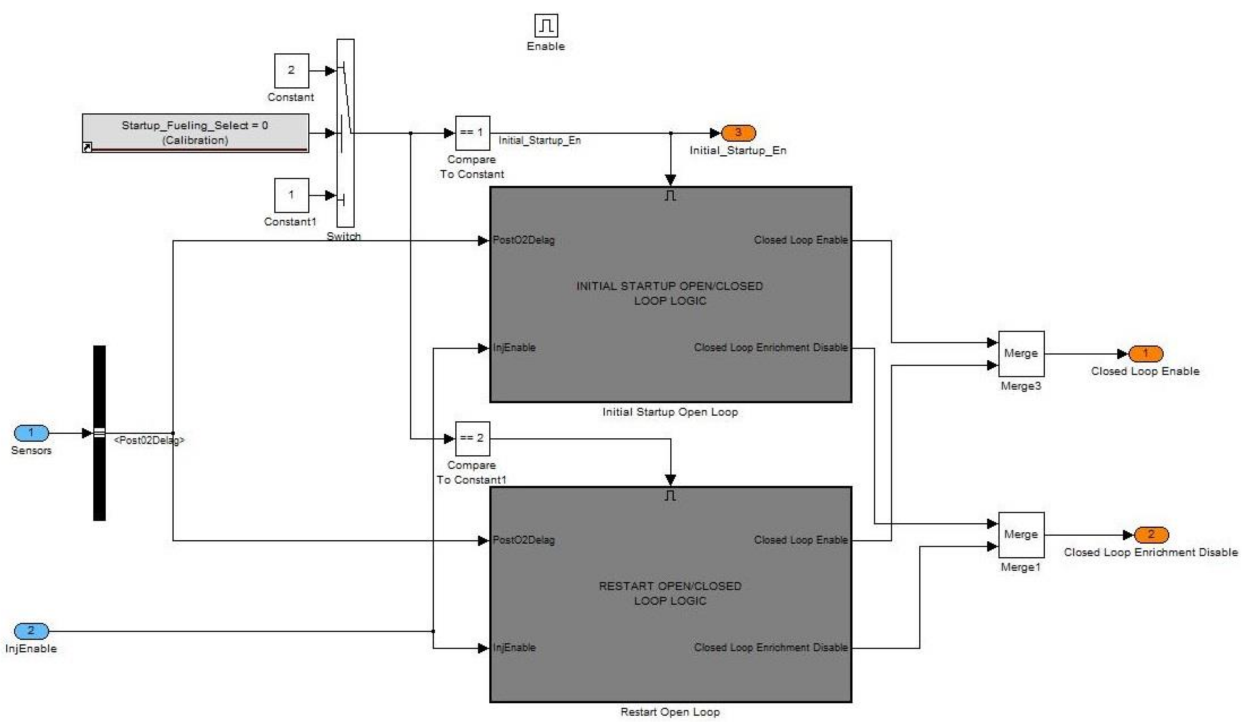


Figure A2: Closed-loop Threshold Subsystems

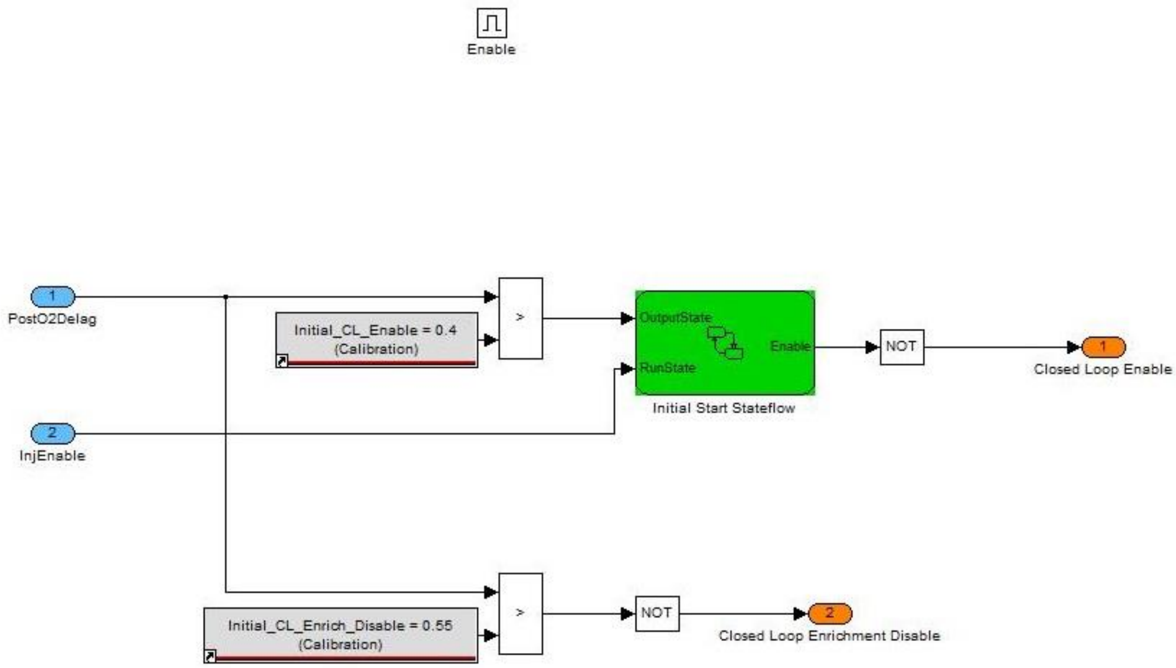


Figure A3: Cold Closed-loop Threshold Logic

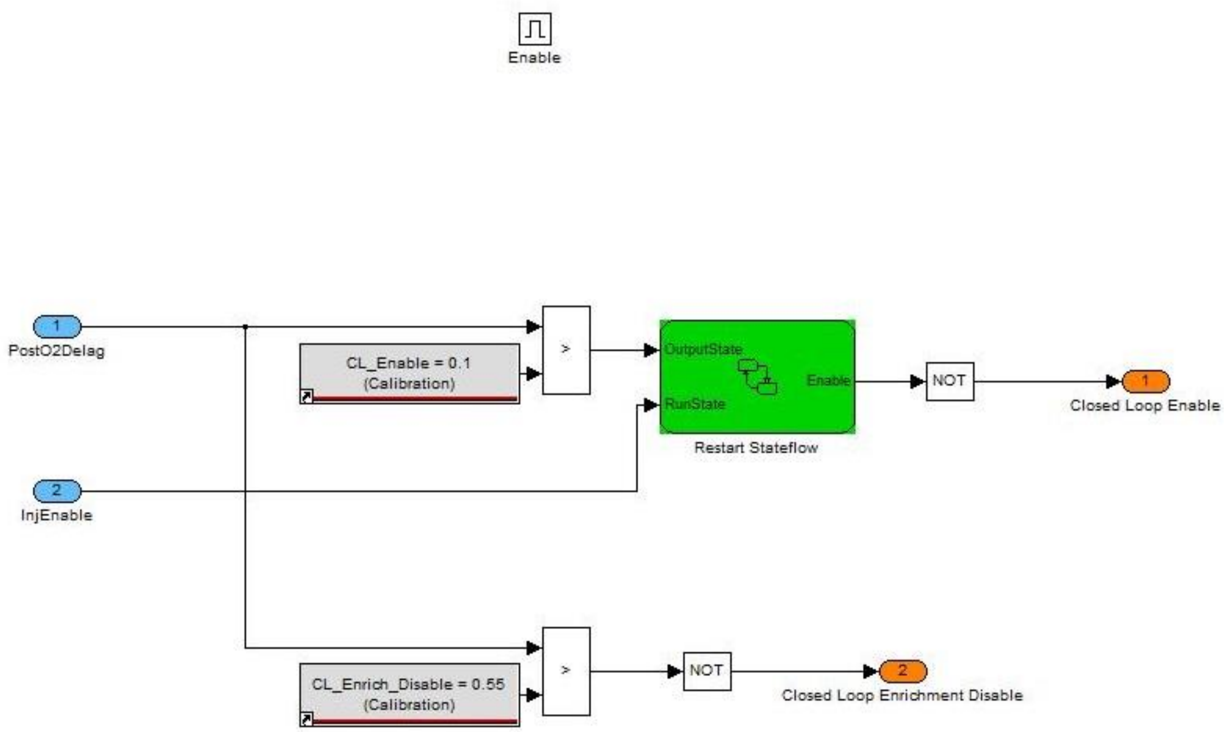


Figure A4: Warm and Hot Closed-loop Threshold Logic

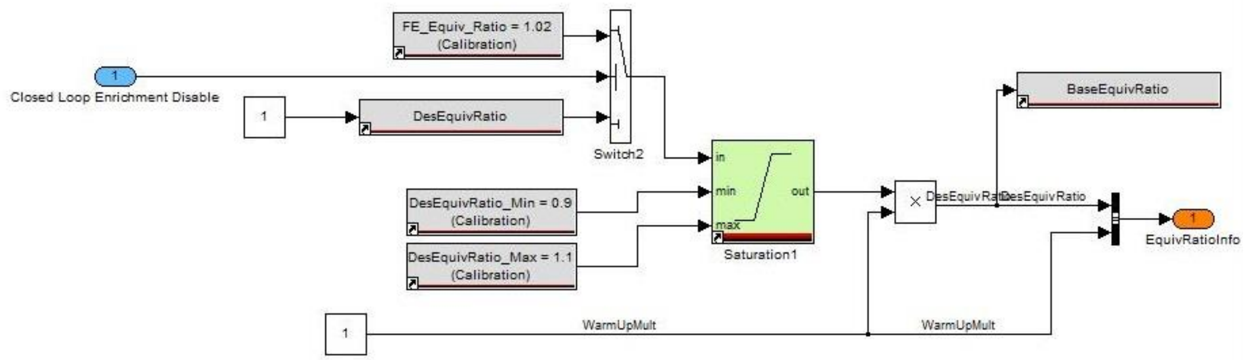


Figure A5: Closed-loop Desired EQR Logic

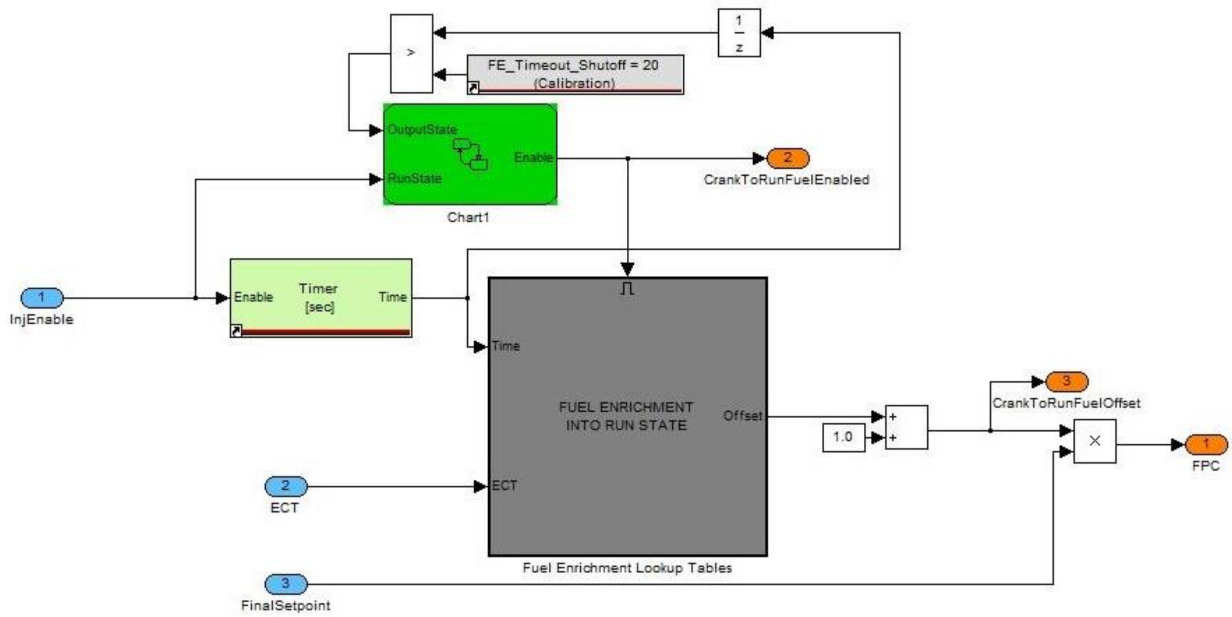


Figure A6: Fuel Enrichment Lookup Table Subsystem

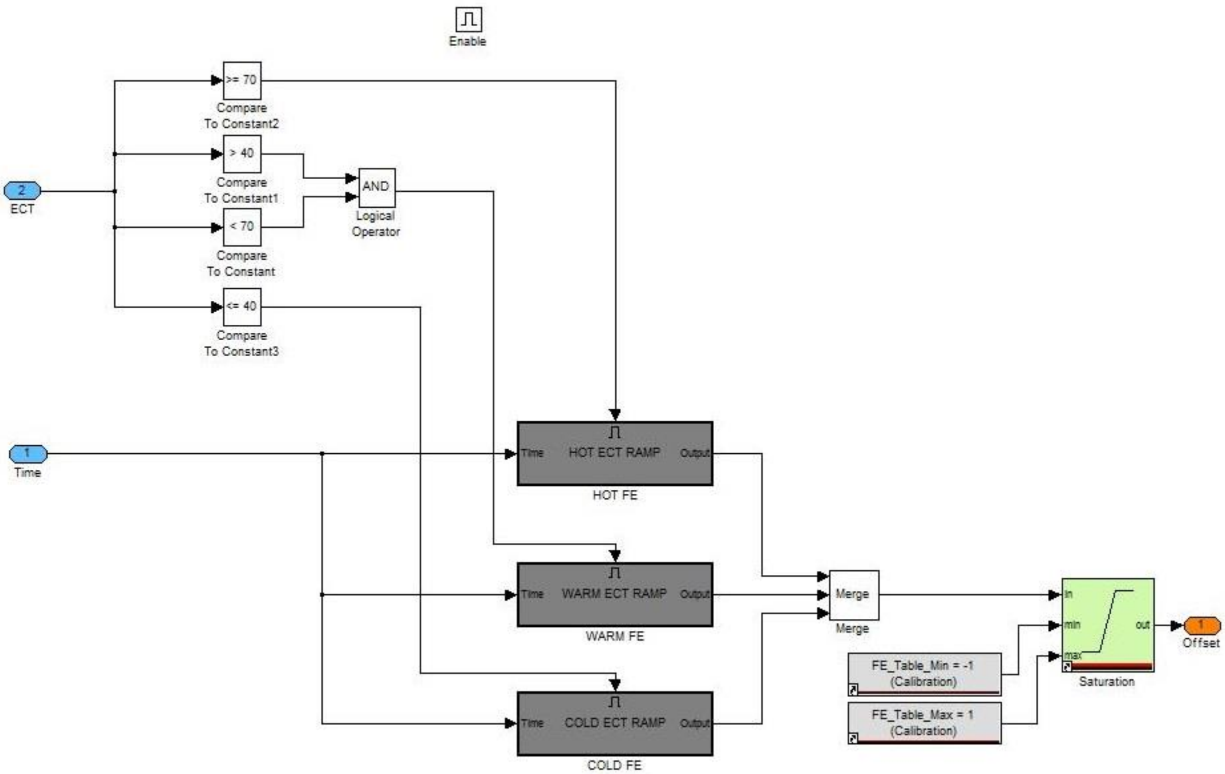


Figure A7: Fuel Enrichment Lookup Table Logic